# Geoindicators Scoping Report for White Sands National Monument

## Strategic Planning Goal Ib4

**January 28-30, 2003**
**Alamogordo, New Mexico**

**Compiled by Katie KellerLynn**
**March 2003**

## Contents

# Scoping Summary

## Introduction

A geoindicators scoping meeting for White Sands National Monument (WHSA) was held on January 28-30, 2003. Locations for the meeting and field trips included White Sands National Monument, Holloman Air Force Base, White Sands Missile Range, and New Mexico Museum of Natural History and Science. Participants included staff from White Sands National Monument, other National Park Service divisions and units, New Mexico Bureau of Geology and Mineral Resources, U.S. Geological Survey, Holloman Air Force Base, and other geologists and resource experts.

### Purpose of meeting

The purpose of the meeting was fourfold: (1) identifying significant geological processes and features that are part of the park's ecosystem, (2) evaluating human influences on those processes and features, and (3) providing recommendations for studies to support resource management decisions, geologic inventory and monitoring projects, and research to fill information gaps. The scoping meeting was designed to use the participants' expertise and institutional knowledge and build on the synergy of the participants through field observations, group discussion, and the exchange of ideas.

### Government Performance and Results Act (GPRA) Goal Ib4

This meeting satisfies the requirements of the GPRA Goal Ib4, which is a knowledge-based goal that states, "Geological processes in 53 parks [20% of 265 parks] are inventoried and human influences that affect those processes are identified." The goal was designed to improve park managers' capabilities to make informed, science-based decisions with regards to geologic resources. It is the intention of the goal to be the first step in a process that will eventually lead to the mitigation or elimination of human activities that severely impact geologic processes, harm geologic features, or cause critical imbalance in the ecosystem.

Because GPRA Goal Ib4 inventories only a sampling of parks, information gathered at White Sands National Monument may be used to represent other parks with similar resources or human influences on those resources. Findings may be used for Servicewide evaluations.

### Geoindicators background information

An international Working Group of the International Union of Geological Sciences developed geoindicators as an approach for identifying rapid changes in the natural environment. The National Park Service uses geoindicators during scoping meetings as a tool to fulfill GPRA Goal Ib4. Geoindicators are measurable, quantifiable tools for assessing rapid changes in earth system processes. Geoindicators evaluate 27 earth system processes and phenomena (Appendix A) that may undergo significant change in magnitude, frequency, trend, or rates over periods of 100 years or less and may be affected by human actions (Appendix B). Geoindicators guide the discussion and field observations during scoping meetings (Appendix C). The geoindicators scoping process for the National Park Service was developed to help determine the studies necessary to answer management questions about what is happening to the environment, why it is happening, and whether it is significant.

The health and stability of an ecosystem is evaluated through the geoindicators scoping process. The geologic resources of a park—sand dunes, canyons, glaciers, caves, beaches, volcanoes, etc.—provide the physical foundation required to sustain the biological system. Geologic processes create topographic highs and lows. They affect water and soil chemistries, and influence soil fertility, hillside stability, and the flow styles of surface water and groundwater. These factors, in turn, determine where and when biological processes occur, such as the timing of species reproduction, the distribution of habitats, and the productivity and type of vegetation. Geologic processes are also factors in the response of ecosystems to human impacts (Appendix D).

### Park selection

The geoindicators scoping meeting at White Sands National Monument grew out of a technical assistance request, which park managers submitted to the Geologic Resources Division (GRD). Park managers requested input, including research ideas, about the Monument's geologic resources for their Resource Management Plan (RMP). Staff at GRD recognized that the geoindicators scoping process could satisfy this request, and it was agreed to carry out a scoping meeting. The information gained from the scoping meeting will also aid managers in park planning, specifically their General Management Plan (GMP) in 2004.

Additionally, White Sands National Monument was selected for is its unique geologic resources and suitability for fulfilling the GPRA Goal Ib4. For instance, the entire continental dune system (one of only four in the National Park System) is preserved in the Monument and contiguous federal lands. Human use was also a factor for selection and provided an opportunity to look at potential impacts from military activities. In actuality, the security associated with the surrounding military facilities has served as a means for preserving the Monument (See Appendix E and Appendix F).

## Summary of Results

During the scoping meeting, geoindicators appropriate to White Sands National Monument were addressed. Of the 27 geoindicators (Appendix A), 18 were recognized as on-going processes in White Sands National Monument. The issues surrounding each geoindicator were identified, and participants rated each one with respect to the importance to the ecosystem and human influences (See Geoindicators table). Park staff rated the significance for park management. A compilation of the notes taken during the scoping session (Appendix G) and the opening session and field trips (Appendix H) are included in the appendices. These notes highlight additional information regarding geoindicators that may be useful to park managers.

Geoindicators table for White Sands National Monument

| GEOINDICATORS | Importance to park ecosystem | Human influence on indicator | Significance for management |
|---|---|---|---|
| **AEOLIAN** | | | |
| Dune formation and reactivation | 5 | 1 | 5 |
| Dust storm magnitude, duration, and frequency | 2 | 1 | 1 |
| Wind erosion | 5 | 1 | 3 |
| **GROUNDWATER** | | | |
| Groundwater chemistry in the unsaturated zone | 5 | 1 | 5 |
| Groundwater quality | 1 | 1 | 1 |
| Groundwater level | 5 | U | 5 |
| **SURFACE WATER** | | | |
| Lake levels and salinity | 5 | 1 | 5 |
| Streamflow | 3 | 3 | 3 |
| Surface water quality | U | U | U |
| Wetlands extent, structure, and hydrology | 3 | 1 | 3 |
| **SOILS** | | | |
| Soil quality | 4 | 5 | 4 |
| Soil and sediment erosion | 5 | 5 | 4 |
| Desert surface crusts and fissures | 5 | 1 | 3 |
| **TECTONICS & LANDSLIDES** | | | |
| Seismicity | 1 | 1 | 1 |
| Slope failure | 1 | N/A | 1 |
| **OTHER** | | | |
| Geothermal activity* | | | |
| Karst activity | N/A | 3 | 3 |
| Sediment sequence and composition** | 2 | U | 3 |
| N/A - Not Applicable<br>1 - LOW influence on, or utility for<br>3 - MODERATELY influenced by, or has some utility for<br>5 - HIGHLY influenced by, or with important utility for<br>U - Unknown; may require study to determine applicability<br>NOTE: 2 and 4 are also ranking options | *See section on geothermal activity in Appendix G<br>**Sediment sequence and composition is a tool with significance for enhancing the information base of the park's ecosystem, identifying human influences on the ecosystem, and providing data for management decisions and planning | | |

## Significant geoindicators

The geoindicators with (1) importance to White Sands National Monument's ecosystem, (2) significant human influences, and (3) significance for park management are listed below. For each category, geoindicators receiving a rating of three or higher are highlighted (See Geoindicators Table). The discussion of geoindicators that received a lower rating is captured in Appendix G.

### *Geoindicators with importance to park ecosystem*

**Dune formation and reactivation**
White Sands is the largest gypsum dune field in the world. There are approximately 275 total square miles of dunes, with 115 square miles (about 40%) located within White Sands National Monument. The white sands are the major driver of the ecosystem and the species within it; for instance, much that some "local populations" have adapted their color to match the sands.

Dune formation and reactivation cannot be adequately discussed without including the relationship of groundwater. Groundwater quality is poor for consumption but important to dune formation and reactivation. The highly saline groundwater affects production of gypsum, which is the primary constituent of the dunes. If the salinity balance is changed, the dune system is changed. In short, less salinity in the dune system, results in less gypsum and less material for dune formation. The saline groundwater also precipitates minerals within the wind blown sand. Because the wind is able to deflate the sand down to the level where moisture from the groundwater continues to cement the sand grains, the elevation of the interdunes is controlled by the groundwater level and salinity.

**Wind erosion**
White Sands National Monument consists of a landscape that is shaped by wind erosion. The transport and storage of sand are also significant for the overall aeolian dune system. The two principal features in the Monument, the gypsum dunes and Lake Lucero, attest to the past and present activity of wind erosion. Although partially refilled now, Lake Lucero is a 60-feet-deep depression created by wind erosion. Wind, gypsum, groundwater, and vegetation are all significant variables in this dune field ecosystem dominated by wind erosion.

**Groundwater chemistry in the unsaturated zone**
In the context of the ecosystem of White Sands National Monument, the unsaturated zone is highly significant and includes not only groundwater chemistry but physical and microbiotic components. Dune stability is a function of the capillary attraction of groundwater and the wicking nature of sand in the unsaturated zone. Groundwater in the unsaturated zone, and the associated water holding capacity of the dunes, are important for plants, burrowing animals, and soil formation.

**Groundwater level**
Groundwater level is a major controlling factor for dune movement. Vegetation and soil crusts play roles in dune stability, but groundwater level is the primary determinant as to whether the dunes are stable or active. If the water table is lowered through natural or anthropogenic means, the dunes will become more active.

**Lake levels and salinity**
Lake Lucero playa is the Monument's second most important asset after the dunes. The shallow lake is concentrated in the deepest part of the basin. The lake level and salinity of Lake Lucero are controlled by evapo-transpiration. Although the ultimate source of gypsum is the Paleozoic-age rocks exposed in the San Andres Mountains to the west of the Monument, another source is the gypsum-charged groundwater beneath Lake Lucero. Hence, Lake Lucero is part of the overall dune system and is linked to the regional groundwater system.

**Streamflow**
During the scoping session, discussion surrounding streamflow concentrated on Lost River, an ephemeral stream. Lost River is the only stream that enters the Monument. Some arroyos on the west side of the Monument run during storm events; otherwise streamflow is limited. Pup fish—a state-listed endangered species—live in the Lost River, outside the Monument's boundary, however.

More generally speaking than streamflow, surface water is important to the ecosystem. Surface water is affected by annual rainfall cycles, which include extreme storm events. Annual rainfall cycles impact cyanobacteria "blooms," plant and animal species, and the playa system.

**Wetlands extent, structure, and hydrology**
Wetlands serve as an indicator of long-term precipitation trends. In desert environments, the existence of wetlands is significant because of the scarcity of water. There is anecdotal evidence that wetlands are being lost. Typically, wetlands are areas of high biodiversity, and the scarcity of wetlands increases their importance to plants and wildlife as a source of water.

**Soil quality**
Soil quality is the ability of soil to function. Retaining soil quality is important to the ecosystem in order that water, nutrients, and stability are supplied to plants. The soils in the Monument are gypsum-rich. They host sparse vegetation, yet the vegetation is highly diverse.

**Soil and sediment erosion**
Soil and sediment erosion is a naturally-occurring process in White Sands National Monument. Obviously, wind erosion, as mentioned earlier, is a driver of the ecosystem. Soil and sediment erosion by water also plays a role. The piedmont landforms, called bajadas, are evidence of this. Bajadas are a coalesced system of alluvial fans. They distribute water and have distinct plant communities and soil types. Bajadas are the recharge area for water to the basin.

**Desert surface crusts and fissures**
Soil crust occupies an intermediate ecological position between active dunes and heavily vegetated surfaces in White Sands National Monument. Soil crusts are indicators of ecosystem stability, health, and climate change. They are critical to plant growth because they fix nitrogen into the system and bind soil. Soil crusts can either promote water infiltration (on silty soils) or increase runoff (on sandy soils). Both these attributes are important for the dune ecosystem. Filaments of cyanobacteria are hydrophobic, so crusts made of cyanobacteria promote lateral redistribution of water.

### *Geoindicators with significant human influences*

**Streamflow**
There is minimal streamflow in White Sands National Monument. The only stream that intermittently flows into the Monument is Lost River, which has been dewatered by the city of Alamogordo and ranching. Water that historically would have flowed in Lost River is now intercepted by spring boxes in the Sacramento Mountains. In addition, population growth in the area has caused increased water use and lowered water levels of Lost River.

Military-owned roads and culverts upslope of the Monument have changed the flow regime originating in the bajada areas along the western boundary. Roads serve as berms and inhibit surface flow across the alkali flats area. Culverts concentrate flow and increase erosion. Of particular concern is erosion of archeological sites impacted by runoff from under-engineered roads, primarily during storm events, and water pathways created by fiber optic lines.

**Soil quality**
Overgrazing and historic ranching practices have hindered the ability of soil to function in White Sands National Monument. With respect to modern practices, soil quality is being lost on the west side of the Monument through accelerated erosion caused by human impacts (e.g., culverts and roads).

**Soil and sediment erosion**
Changes in plant communities have occurred in White Sands National Monument. These changes have been attributed in part to historic ranching practices that led to overgrazing, and ultimately soil and sediment erosion. Changes include loss of fine plant material and a transformation from grasslands (typical in the 1800s) to shrublands (typical today). In general, shrublands reflect increased aridity and greater potential for soil and sediment erosion.

Modern practices, such as under-engineered roads mentioned previously, accelerate downcutting. In addition, fiber optic cables cut and buried in straight lines serve as “speedways” for water that causes accelerated erosion. Additionally, a concentration of precipitation-runoff along old roads and trails on the west-side bajadas is notable. For example, along the trail east to Lake Lucero, several areas of gully erosion occur. This accelerated erosion is not related to the gullies caused by road culverts or fiber-optic lines.

**Karst activity**
Karst-like natural dissolution processes frequently occur in the cemented gypsic and calcic soils of the Tularosa Basin, resulting in collapsed areas, with little if any prior surface indication. Openings such as desiccation cracks or animal burrows provide starting points where water collection causes significant subsurface dissolution. Human activities have caused a new form of this process in the Monument. Buried water and utility lines and poorly-compacted construction excavations provide a less-dense matrix which increases water infiltration and saturation below grade. Inadvertent water line leaks exacerbate this condition. The water, whether from natural sources or leaks, dissolves the gypsum. At the Monument, as well as nearby developed areas such as Holloman, parking lot edges, curbs, utility trenches, and buildings are being undercut by this process. The Monument’s historic Visitor Center appears to be subsiding, probably due to sheer mass and soil compaction, but possibly due to dissolution processes.

### *Geoindicators with management significance*

**Dune formation and reactivation**
The gypsum dunes are the primary resource in White Sands National Monument. The Monument was set aside in 1933 for the preservation of the white sands. Therefore, the dune formation and reactivation geoindicator has high significance for management. In addition to preserving the dunes, managers are responsible for interpreting the dunes to the public and ensuring public access.

**Wind erosion**
White Sands National Monument consists of a landscape shaped by wind erosion. Wind erosion, and the associated processes of sand transport and deposition, has management significance because of the prevalence of these processes on the landscape. In order to keep the dunes accessible to all visitors, staff time is used to keep the Loop Road open, which is constantly affected by aeolian processes (i.e., wind erosion, sand transport, and sand deposition). Furthermore, wind erosion is a consideration in future development of facilities and maintenance of current facilities, e.g., roads, trails, fences, and restrooms. Additionally, wind erosion is a primary story for interpretation. It also impacts cultural resources, for example, by eroding hearth sites.

**Groundwater chemistry in the unsaturated zone**
Managers recognize the important relationship between groundwater in the unsaturated zone—including chemical, physical, and microbiotic components—and the gypsum dunes. This relationship requires more study, but mangers realize the significance for dune formation and reactivation. In addition to the dunes, groundwater in the unsaturated zone affects other resources, such as plant and animal species, which also have management significance.

**Groundwater level**
As a major controlling factor of dune activity, groundwater has high management significance. In short, if the water table is lowered, the dunes may become more active. Furthermore, interdune areas may be affected. If the water table is lowered, there may be fewer plants and more wind erosion, depending on how durable the interdune surface crust is.

**Lake level and salinity**
The level and salinity of Lake Lucero, as part of the overall dune system, has high management significance. Being able to accurately interpret Lake Lucero and the source of gypsum sand is quite significant. Research findings on Lake Lucero will have a major influence on interpretive materials and presentations.

**Streamflow**
Roads, culverts, and fiber optic lines have changed natural flow regimes, especially flow from bajada slopes along the western boundary. Concentrated flow through culverts has affected archeological sites in the Monument. The principal damage has been done to these sites, and damage is now incremental. Mitigating further damage to these sites is a management concern.

**Wetlands extent, structure, and hydrology**
Park managers have a general concern that wetlands have been lost, apparently due to drought. There is anecdotal evidence that certain wetland species were much more abundant in the recent past. For example, frogs were heard from the housing area in the 1980s. Wetlands are naturally-driven systems with minimal human impacts in White Sands National Monument. Hence, there

is not much mitigation for park managers. Nevertheless, managers are concerned about the loss of wetlands and riparian species.

**Soil quality**
There is concern that the soil on the west side of the Monument (about 10% of the Monument) is losing quality. In particular the loss of fine material and water-holding capacity has been identified.

**Soil and sediment erosion**
Soil and sediment erosion is a natural process, but concerns arise when soil and sediment erosion is human-caused and detrimental to park resources. For instance, poorly-engineered culverts on roads cause accelerated erosion that has damaged cultural resources, e.g., the Huntington Site, an archeological site in the northwest corner of the Monument. Soil and sediment erosion is an issue for park mangers as they come into compliance with standards for archeological sites.

**Desert surface crusts and fissures**
Soil crusts in White Sands National Monument appear robust, and potential problems are unknown. Managers recognize the key role that soil crusts play in the ecosystem, but threats seem minimal. Managers require more information in order to give a higher rating than moderate for management significance.

**Karst activity**
Human-induced karst activity has moderate significance for park managers. Stabilizing the Visitor Center and mitigating further water leaks is important with respect to the overall maintenance of park facilities.

**Sediment sequence and composition**
Sediment sequence and composition is a "tool" that can provide necessary background information and a past context of both natural processes and human activities. Analysis of sediment sequence and composition has been identified as a means for understanding long-term trends in an ecosystem and identifying human influences on the ecosystem. As such, sediment sequence and composition can provide data for management decisions and planning. For example, sediment cores that record the evolution of Lake Lucero would provide historical and baseline information that would be useful for resource management, park planning, and interpretation.

## Summary of Recommendations

The following summary of recommendations lists ideas that were discussed during the January 28-30, 2003 scoping meeting held in White Sands National Monument. The summary includes recommendations for inventory, monitoring, research, and mitigation. Recommendations are not listed in any order of priority.

### Recommendations for inventory

**1. Compile references and data on dunes**
A useful place to start in order to better understand dune processes is compiling and organizing available information. The body of literature on the dunes may be substantial and will contain

some classic works (McKee 1966, 1971). Information will also include aerial photographs and satellite images.

It is suggested that an upper-level undergraduate or graduate student with training in aeolian geomorphology could complete this task and provide necessary annotations and explanations to park staff. Funding for such a project may be available through the National Park Service Geoscientist-in-the-Parks (GIP) or Geologic Resources Inventory (GRI) programs.

Contacts
- Judy Geniac, GIP Program Manager, Geologic Resources Division, judy_geniac@nps.gov, 303-969-2015
- Bob Higgins, Chief, Science and Technical Assistance Branch, Geologic Resources Division, bob_higgins@nps.gov, 303-969-2018

References

McKee, E.D., 1966, Structures of dunes at White Sands National Monument, New Mexico (and a comparison with structures of dunes from other selected areas): Sedimentology, v. 7, no. 1, Special Issue, 136 p.

McKee, E.D., 1971, Growth and movement of dunes at White Sands National Monument, New Mexico: U.S. Geological Survey Professional Paper 750-D, p. 108-114.

**2. Gather baseline information on groundwater level**
At present it is unknown if current and potential water supply needs of the basin inhabitants will affect shallow groundwater levels at the Monument. Furthermore, groundwater level has been identified as a major controlling factor on dune activity. It is important, therefore, to gather baseline data on groundwater level to distinguish human use/drawdown from natural (seasonal and annual) fluctuations. Park managers need basic information about the local aquifers to respond in an informed way to the growth and development in the Tularosa Basin and the effects on park resources.

**3. Inventory soils**
The scale at which the existing soils map (Neher and Bailey, 1976) was produced is not useful for making management decisions. It is suggested that the Monument be remapped at a more useful scale. The mapping project should include soil crusts.

Contact
- Pete Biggam, NPS Soil Scientist, Natural Resources Information Division, pete_biggam@nps.gov, 303-987-6948

Resources
- NRCS and Soil Quality Institute in Las Cruces
- Jornada Experimental Range Station

Reference

Neher, R.E. and Bailey, O.F., 1976, Soil survey of White Sands Missile Range, New Mexico, parts of Otero, Lincoln, Doña Ana, and Soccorro counties:  U.S. Department of Agriculture, 64 p.

**4.  Gather baseline formation on surface water quality**
Park managers lack information about the effects of surface water quality on the ecosystem; moreover, human influences are unknown. In general, water quality, which is poor for consumption, is dominated by the close proximity of gypsum to surface water bodies throughout the Monument, interior drainage, and climatic factors such as the dominance of evaporation. Thus, approaches to inventorying surface water quality will be strongly influenced by sporadic precipitation/runoff events which may momentarily improve overall water quality by dilution. The ephemeral nature of surface water at White Sands National Monument makes sampling for surface water quality difficult. Innovative techniques, such as sampling the leaves of salt cedar near Lost River, are being used by the U.S. Geological Survey. Sources of contaminants may be limited to nearby military facilities.

Contact
- Rick Huff, U.S. Geological Survey, Las Cruces, gfhuff@usgs.gov, 505-646-7950

**5.  Inventory wetlands**
A comprehensive inventory of wetlands has not been performed. Yet, there is anecdotal evidence that wetlands, and thereby wetland species, are being lost. If an inventory of wetlands is undertaken, it is suggested that the protocols and classification used in a nine-year study on the White Sands Missile Range be adapted. There are also aerial photographs from the 1940s, 1984, and 1996 that may be useful background information for an inventory of wetlands.

Contact
- Joel Wagner, Hydrologist NPS Water Resources Division, joel_wagner@nps.gov, 303-969-2955
- Robert G. Myers, White Sands Missile Range, myersr@wsmr.army.mil, 505-678-8751

**6.  Compile information on soil crusts**
Various applicable sources of data on soil crusts exist:  (1) data from vegetation plots in White Sands Missile Range, (2) data from Holloman Air Force Base, (3) data from a study of ATV tracks in 2000 and 2002 in the Monument, and (4) AVIRIS imagery from University of Texas at El Paso. It is suggested that a database of this information be developed in order to analyze what is known about resilience, recovery rates, overall spatial distribution, and spatial distribution of various types of crusts.

Once this information is compiled and analyzed, decisions can be made regarding needed mapping and future monitoring. A possible plan of action might be:  Samples of the crusts, which are growing in a laboratory setting at New Mexico State University, are imaged in the laboratory at University of Texas at El Paso with a hand-held/laboratory instrument to obtain the spectra of wet samples. After a spectra is obtained, watering stops, and the crusts are “imaged” as they dry out. In this way, a database is established to help interpret the satellite imagery. The AVIRIS image is for one point in time. Information gained from this method using AVIRIS will be analyzed and potentially extended to other satellite platforms which are available more often.

Contacts

- Dr. Hildy Reiser, Natural Resources Manager, Holloman Air Force Base, Hildy.Reiser@holloman.af.mil, 505-572-3931
- Phil Goodell, University of Texas at El Paso, goodell@utep.edu, 915-747-5968
- Curtis Monger, New Mexico State University, cmonger@nmsu.edu, 505-646-1910

## Recommendations for monitoring

**1. Monitor lake levels and salinity of Lake Lucero**

Lake Lucero is an integral part of the dune ecosystem. It is also linked to the regional groundwater system. Monitoring of lake levels and salinity would provide insight into the interrelationships between Lake Lucero, dune processes, and groundwater. Data gained through monitoring would help answer many questions, such as, (1) What salts are produced in Lake Lucero?, (2) When are they produced?, (3) What are the relative amounts of groundwater and surface water?, (4) How do changes in lake level affect salinity?, (5) How do lake levels correspond to the regional water table aquifer and to potential perched aquifer(s) of the dune field?

It is recommended that a team of subject and resource experts be formed to develop a monitoring program for Lake Lucero.

Potential members

- Rip Langford, University of Texas at El Paso, langford@utep.edu, 915-747-5968
- Andrew Valdez, Great Sand Dunes National Park, andrew_valdez@nps.gov, 719-378-2312
- Anne-Marie Matherne, U.S. Geological Survey, Albuquerque, amatherne@usgs.gov, 505-830-7971
- Rick Huff, U.S. Geological Survey, Las Cruces, gfhuff@usgs.gov, 505-646-7950

**2. Monitor extreme storm events**

As mentioned previously, the ephemeral nature of surface water at White Sands National Monument makes sampling of surface water difficult. In order to adequately record “vital statistics” (e.g., amount, quality, duration) of surface water in the Monument, a specialized approach needs to be taken. Summer storm events, in which the majority of annual precipitation falls, need to be monitored. Since storms are very localized, a SWAT approach would need to be developed. In addition, using crest stage gages to measure streamflow in inaccessible areas should be considered.

Contacts

- Rick Huff, U.S. Geological Survey, Las Cruces, gfhuff@usgs.gov, 505-646-7950
- Pete Penoyer, NPS Water Resources Division, pete_penoyer@nps.gov, 970-225-3535

**3. Monitor groundwater level and quality**

The importance of groundwater to the ecosystem has been identified, but the actual mechanics and processes need to be better understood. Basic data, such as groundwater level and quality, which would enhance the overall information base could be gathered within the Monument. A network of monitoring wells could be established. The six existing wells in the Monument could be used more extensively for data gathering. Such a network has been established in Great Sand

Dunes National Park, which could serve as a model for White Sands. There may be a seasonal cycle, so monitoring would need to capture this.

Contacts

- Rick Huff, U.S. Geological Survey, Las Cruces, gfhuff@usgs.gov, 505-646-7950
- Bruce Allen, New Mexico Bureau of Geology and Mineral Resources, allenb@gis.nmt.edu, 505-366-2531
- Andrew Valdez, Great Sand Dunes National Park, andrew_valdez@nps.gov, 719-378-2312

**4. Monitor gully erosion along trails and roads**

It is suggested that erosion along trails, for example west of Lake Lucero, be addressed by park managers. This accelerated erosion is not related to the gullies caused by road culverts or fiber-optic lines. For example, the gullies along the trail to Lake Lucero are providing fresh exposures which could result in more information about Lake Otero or fossils in lake deposits. These exposures may also provide interpretive opportunities during walks to Lake Lucero. Beginning to document changes at present would help with future interpretive signs (i.e., historic changes in the bajada).

Contact

- Dave Love, New Mexico Bureau of Geology and Mineral Resources, dave@gis.nmt.edu, 505-835-5146

## Recommendations for research

**1. Study the relationship between dunes and groundwater**

During the geoindicators scoping meeting at White Sands National Monument, it became clear that a better understanding of the relationship between dune processes and groundwater dynamics is needed. For example, there is anecdotal evidence for the significance of the unsaturated zone on dune stability, but the mechanism is not well understood. It is also suspected that the high salinity content of the groundwater is important for gypsum production and dune formation, but again the mechanism needs further study. In addition, studying the local, possibly perched, groundwater conditions of the dune field may provide a broader understanding of the groundwater resources of the basin.

A regional, basin-wide conceptual model needs to be developed in order to better understand groundwater dynamics and its relationship to the overall aeolian system. The U.S. Geological Survey is in the process of developing a groundwater model for the Tularosa Basin. The first draft is under review at present, but completion is anticipated to take a year or more. Once this regional model is completed, “telescoping” to the park-scale is possible. This groundwater model would be part of a model of the entire aeolian system.

It is suggested that park staff solicit scientists to submit a research proposal for consideration. There is potential funding through the Inventory and Monitoring Network and other NPS sources, as well as cooperative scientific efforts and cost share with partners (e.g., U.S. Geological Survey, U.S. Department of Defense, New Mexico Bureau of Geology and Mineral Resources, and area universities).

Contacts

- Rip Langford, University of Texas at El Paso, langford@utep.edu, 915-747-5968
- Rick Huff, U.S. Geological Survey, Las Cruces, gfhuff@usgs.gov, 505-646-7950
- Robert G. Myers, White Sands Missile Range, myersr@wsmr.army.mil, 505-678-8751
- Pete Penoyer, NPS Water Resources Division, pete_penoyer@nps.gov, 970-225-3535
- Steve Fryberger, sfandflf@omantel.net.om
- Bill Reid, Chihuahuan Desert I & M Network, bill_reid@nps.gov

**2. Study present significance, history, and paleontology of Lake Lucero**

Lake Lucero has not been sufficiently studied to fully understand its importance to the Tularosa Basin and White Sands National Monument. Furthermore, Lake Lucero, and its Pleistocene predecessor Lake Otero, has an interesting geologic history that requires further study. Information gained from an in-depth study of this resource would allow park staff to better understand, manage, and interpret Lake Lucero. Information would also aid in understanding the present dynamics of Lake Lucero, which factor into dust storms and what salts are produced at what times. In addition, it is recommended that the paleontology of Lake Lucero be studied, as well as investigating whether tracks or bones (as well as microfossils in cores) might be on the Monument (Appendix I).

Extracting and analyzing a sediment core from Lake Lucero would be a significant step toward determining Lake Lucero's history and evolution. A multi-disciplinary approach to analysis should be considered and would thereby include stratigraphy, mineralogy, palynology, limnology, and micropaleontology and gain the most information possible. Also some fraction of the slabbed core should be retained for future analysis and display purposes (e.g., learning center display at monument). Such data would provide needed background information and a past context of both natural processes and human activities.

Contacts

- Adrian Hunt, New Mexico Museum of Natural History, ahunt@nmmnh.state.nm.us, 505-841-2841
- Peter Scholle, New Mexico Bureau of Geology and Mines as Resources, pscholle@gis.nmt.edu, 505-835-5302
- Rip Langford, University of Texas at El Paso, langford@utep.edu, 915-747-5968
- Rick Huff, U.S. Geological Survey, Las Cruces, gfhuff@usgs.gov, 505-646-7950
- Pete Penoyer, NPS Water Resources Division, pete_penoyer@nps.gov, 970-225-3535
- Steve Fryberger, sfandflf@omantel.net.om

**3. Prepare geomorphic and chronosequence map of dunes**

A map that identifies the various generations of dunes, ranging from active dunes to the oldest fossil dunes, needs to be made. This map could build on work by Building on maps by Seager (1987) and Fryberger (1999). Additional dating needs to be performed using radiocarbon and thermoluminescence methods. A chronosequence of soil formation on the dunes needs to be investigated. This will include vegetative states, desert crusts, soil horizons, and stable isotopic signatures of authigenic soil minerals. To supplement this study, land surfaces buried by dunes and by alluvial sediments west of Lake Lucero need to be investigated. In particular, fossil pollen, phytoliths, and carbon isotopes of paleosols need to be documented.

References

Fryberger, S.G., 1999, accessed February 4, 2003, Reconnaissance geomorphic map of the active White Sands dune field, New Mexico, *in* Geological overview of White Sands, chapter 2, Quaternary geology, figure 2-17A: <http://www.davidjonline.com/geows/index.html>.

Seager, W.R., J.W. Hawley, F.E. Kottlowski, and S.A. Kelley, 1987, Geology of east half of Las Cruces and northeast El Paso 1x2 degree sheets, New Mexico: New Mexico Bureau of Mines and Mineral Resources Geologic Map 57, 1:125,000.

## Recommendation for mitigation

**1. Mitigate further damage to archeological sites caused by human-induced erosion**
Under-engineered roads for extreme storm events and fiber optic lines have caused erosion to archeological sites in the Monument. It is suspected that the principal damage from Range Road 7 to these sites has been done, and damage is now incremental. It is much more likely that old fiber optic cables will be repaired and replaced and new cable added, than the road being modified. Repairing, replacing, and adding fiber optic cables has more potential to introduce new damage than erosion caused by roads, which continues at a more moderate rate.

Park managers desire to mitigate further damage to these cultural resources. The potential for a partnership between White Sands National Monument and White Sands Missile Range was identified during the scoping meeting. It is suggested that park staff pursue this partnership opportunity.

Contacts
- Diane White, Cultural Resource Specialist, White Sands National Monument, diane_white@nps.gov, 505-679-2599 x. 223
- Robert G. Myers, White Sands Missile Range, myersr@wsmr.army.mil, 505-678-8751

## Recommendation for interpretation

The "Park Geological Setting" included in this report was prepared by John Singleton, a Geoscientist-in-the-Park (GIP) in White Sands National Monument in 2001 and used by permission of park staff. Suggestions for improving Appendix F, "Park Geological Setting," can be found in Appendix J. After reviewing this summary, participants suggested that park managers work with the New Mexico Bureau of Geology and Mineral Resources and other resource experts to develop interpretation materials about the geology of White Sands National Monument. In addition to developing materials on the general geology of the Monument, it is suggested that park staff, staff from the New Mexico Bureau of Geology and Mineral Resources, and other resource experts discuss current issues relative to what visitors see during their visit to the Monument. Interpretive materials could be based on the outcome of this discussion. Issues may include the consequences of global climate change to dunes; water issues; impact of humans on park conservation efforts; natural hazards such as dust storms, earthquakes, and debris flows.

Contacts
- Greer Price, New Mexico Bureau of Geology and Mineral Resources, gprice@gis.nmt.edu, 505-835-5752

- Dave Love, New Mexico Bureau of Geology and Mineral Resources, dave@gis.nmt.edu, 505-835-5146
- Steve Fryberger, sfandflf@omantel.net.om

## List of Participants

### White Sands National Monument
Bill Conrod, Natural Resource Specialist
Kathy Denton, Education Specialist
Jessica Kusky, Interpreter
Julie Lockhard, Student Conservation Association Intern
Jim Mack, Superintendent
John Mangimeli, Chief of Interpretation
Diane White, Cultural Resource Specialist

### National Park Service
Bob Higgins, Geologic Resources Division
Greg McDonald, Geologic Resources Division
Lisa Norby, Geologic Resources Division
Pete Penoyer, Water Resources Division
Andrew Valdez, Great Sand Dunes National Park
Bill Reid, Chihuahuan Desert I & M Network

### New Mexico Bureau of Geology and Mineral Resources
Bruce Allen, Field Geologist
Dave Love, Principal Senior Environmental Geologist
Greer Price, Senior Geologist/Chief Editor
Peter Scholle, Director/State Geologist

### U.S. Geological Survey
Rick Huff, Las Cruces
Anne-Marie Matherne, Albuquerque

### Holloman Air Force Base
Andrew "JR" Gomolak, Geologist/Archeologist
Rich Wareing, Chief of Environmental Analysis

### Other Participants
Phil Goodell, University of Texas at El Paso
Adrian Hunt, New Mexico Museum of Natural History and Science
Katie KellerLynn, Geologist/NPS Contractor
Rip Langford, University of Texas at El Paso
Curtis Monger, New Mexico State University
Robert Myers, White Sands Missile Range

## Appendices

**Appendix A: Descriptions of 27 Geoindicators**
**Appendix B: Human Influences**
**Appendix C: Introducing Geoindicators**
**Appendix D: Species Don't Stand Alone—Geology's Role in Ecosystems**
**Appendix E: Park Setting**
**Appendix F: Park Geological Setting**
**Appendix G: Compilation of Notes taken during the Scoping Session**
**Appendix H: Compilation of Notes taken during Opening Session and Field Trip**
**Appendix I: Paleontological Resources at White Sands National Monument**
**Appendix J: Comments on Appendix F, "Park Geological Setting"**

## Appendix A: Description of 27 Geoindicators

Geoindicators have been developed as tools to assist in integrated assessments of ecosystems, as well as for environmental reporting. As descriptors of common earth processes that operate in a variety of settings, geoindicators represent collectively a new kind of landscape metric, one that concentrates on the non-living components of the lithosphere, pedosphere, and hydrosphere, and their interactions with the atmosphere and biosphere (including humans).

**The Geoindicator Checklist:** Geoindicators are available in the form of a checklist that identifies 27 earth system processes and phenomena that are liable to change in less than a century in magnitude, direction, or rate to an extent that may be significant for environmental sustainability and ecological health.

The 27 geoindicators are:

1. Coral chemistry and growth patterns
2. Desert surface crusts and fissures
3. Dune formation and reactivation
4. Dust storm magnitude, duration, and frequency
5. Frozen ground activity
6. Glacier fluctuations
7. Groundwater quality
8. Groundwater chemistry in the unsaturated zone
9. Groundwater level
10. Karst activity
11. Lake levels and salinity
12. Relative sea level
13. Sediment sequence and composition
14. Seismicity
15. Shoreline position
16. Slope failure (landslides)
17. Soil and sediment erosion
18. Soil quality
19. Streamflow
20. Stream channel morphology
21. Stream sediment storage and load
22. Subsurface temperature regime
23. Surface displacement
24. Surface water quality
25. Volcanic unrest
26. Wetlands extent, structure, hydrology
27. Wind erosion

The descriptions of geoindicators that follow were adapted from the geoindicators checklist developed by the International Union of Geological Sciences through its Commission on Geological Sciences for Environmental Planning. Each geoindicator includes a brief description, reasons for its significance to an ecosystem, and examples of human influences from national park settings (when available). The National Park Service uses these descriptions to facilitate discussion during scoping meetings in national parks. The purpose of a scoping meeting is to identify significant geological processes in a park's ecosystem and determine if those processes are being affected by human activities. For each scoping meeting, geoindicators are selected from the list of 27, as appropriate to the terrain and environmental issues under consideration.

## Coral chemistry and growth patterns

**Brief Description**: Corals can be used to monitor environmental changes in the oceans and nearby coastal zone. The health, diversity, and extent of corals, and the geochemical makeup of their skeletons, record a variety of changes in the ocean surface water. These include temperature, salinity, fertility, insolation, precipitation, winds, sea levels, storm incidence, river runoff, and human inputs. Corals in coastal waters are susceptible to rapid changes in salinity and suspended matter concentrations and may be valuable indicators of the marine dispersion of agricultural, urban, mining, and industrial pollutants through river systems, as well as the history of contamination from coastal settlements.

**Significance:** The combination of abundant geochemical tracers, sub-annual time resolution, near-perfect dating capacity, and applicability to both current and past climatic changes establishes corals as one of the richest natural environmental recorders and archives.

**Human influence:** Corals respond to both natural changes in the marine environment and to anthropogenic pollution.

## Desert surface crusts and fissures

**Brief Description:** The appearance or disappearance of thin (mm to cm) surface crusts in playas and depressions in arid and semi-arid regions may indicate changes in aridity. The formation of persistent deep, polygonal cracks in the mud and silt floors of closed basins and depressions may indicate the onset of aridification or severe drought. Surfaces may contain other desiccation features such as sedimentary dikes, evaporite deposits (especially gypsum and halite), adhesion ripples, and large salt polygons.

Physical soil crusts (thin layer with reduced porosity and increases density at the surface of the soil) and biological soil crusts (a living community of lichen, cyanobacteria, algae, and moss growing on the soil surface and binding it together) are also significant indicators of the state of an ecosystem. Recovery of biological crusts may take decades to hundreds of years. The amount and extent of degration to soil crusts are excellent indicators of physical disturbance to an area.

**Significance:** Desert surface crusts are important because they protect the underlying fine material from wind erosion. Physical and biological crusts; in Canyonlands and Arches national parks, for instance; generally help to control wind erosion. Biological crusts fix atmospheric nitrogen for vascular plants; provide carbon to the interspaces between vegetation; secrete metals that stimulate plant growth; capture dust (i.e., nutrients) on their rough, wet surface areas; and decrease surface albedo. Depending on soil characteristics, biological crusts may increase or reduce the rate of water infiltration. By increasing surface roughness, they reduce runoff, thus increasing infiltration and the amount of water stored for plant use.

**Human Influences:** The formation of surface crusts is related primarily to natural causes, but hydrological regimes that affect crust formation and persistence may be altered by human activities, such as river diversion and groundwater extraction. Both physical and biological crusts can be affected by physical disturbances caused by wheeled or tracked vehicles, livestock hooves, and hiking and cycling. The impact is determined by the severity, frequency, and timing of the disturbance and by the size of the disturbed area.

In Arches National Park, grazing practices have impacted physical and biological crusts. Seventy-five percent of the park was grazed until 1974, and cow trespass still occurs. Soil and nutrient cycles have not recovered from this past practice (2002). Trampling by visitors at North and South Window Arch, to “get the perfect picture” or to short-cut to the parking lot, has damaged soil crusts in the area. On the boundary of Arches and Canyonlands national parks, the use of seismic “thumper” trucks during oil and gas exploration created 160 miles of roads and 110 miles of ATV tracks—all of which damaged soil crusts in the area.

## Dune formation and reactivation

**Brief Description:** Dunes and sand sheets develop under a range of climatic and environmental controls, including wind speed and direction, and moisture and sediment availability. In the case of coastal dunes, sea-level change and beach and nearshore conditions are important factors. Organized dune systems and sheets in continental environments form from sediment transported or remobilized by wind action. New generations of dunes may form from sediment remobilized by climatic change and/or human disturbances.

Sand movement is inhibited by moisture and vegetation cover, so that dunes can also be used as an indicator of near-surface moisture conditions. Changes in dune morphology or position may indicate variations in aridity (drought cycles), wind velocity and direction [see wind erosion], or disturbance by humans.

**Significance:** Moving dunes may engulf houses, fields, settlements, and transportation corridors. Active dunes in sub-humid to semi-arid regions decrease arable land for grazing and agriculture. They also provide a good index of changes in aridity. Coastal dunes are important determinants of coastal stability, supplying, storing, and receiving sand blown from adjacent beaches. Dunes play an important role in many ecosystems (boreal, semi-arid, desert, coastal) by providing morphological and hydrological controls on biological gradients.

**Human Influence:** Widespread changes can be induced by human disturbance, such as alteration of beach processes and sediment budgets, destruction of vegetation cover by trampling or vehicle use, overgrazing, and the introduction of exotic species.

Sleeping Bear Dunes National Seashore has a number of prominent dunes (300-400 ft high): Sleeping Bear Dune, Empire Dunes, Pyramid Dunes, Michigan Overlook, and the Dune Climb. Most of these dunes are perched dunes and consist of a relatively thin blanket of sand that has been blown to the top of thick glacial deposits. Foot traffic and social trails have highly modified the Dune Climb and Michigan Overlook, very popular visitor sites. The Dune Climb, once a perched dune, has evolved and migrated off the plateau onto the adjacent lowland.

In Cape Cod National Seashore, migration of the dunes has caused alarm since the 19th century. Dunes have migrated into Pilgrim Lake, over homes in Provincetown, and onto roads. In the 1980s, mitigation efforts were seen as a top priority, and funding was spent on efforts such as pouring asphalt onto the dunes and revegetating the dunes.

## Dust storm magnitude, duration, and frequency

**Brief Description**: The frequency, duration, and magnitude (intensity) of dust storms are gauges of the transport of dust and other fine sediments in arid and semi-arid regions [see wind erosion]. Desert winds carry more fine sediment than any other geological agent. An increased flux of dust has been correlated with periods of drier and/or windier climates in arid regions, historically and from proxy records in ocean and ice cores.

**Significance:** Local, regional, and global weather patterns can be strongly influenced by accumulations of dust in the atmosphere. Dust storms remove large quantities of surface sediments and topsoil with nutrients and seeds. Wind-borne dust, especially where the grain size is less than 10 µm, and salts are known hazards to human health. Dust storms are also an important source of nutrients for soils in desert margin areas.

**Human Influence:** Dust storms are natural events, but the amount of sediment available for transport may be related to surface disturbances such as overgrazing, ploughing, or removal of vegetation. Identified as single events on the scale of days in Arches and Canyonlands national parks, dust storms cause hazardous travel conditions. In addition, dust storms transport contaminated sediment from the Atlas Mine tailings pile (outside park boundary) into the employee housing area in Arches National Park.

## Frozen ground activity

**Brief Description:** In permafrost and other cryogenic (periglacial) areas and in temperate regions where there is extensive seasonal freezing and thawing of soils, a wide range of processes lead to a variety of surface expressions, many of which have profound effects on human structures and settlements, as well as on ecosystems.

These sensitive periglacial features are found around glaciers, in high mountains (even at low-latitudes) and throughout polar regions. The development (aggradation) or degradation of permafrost is a sensitive and early indicator of climate change [see subsurface temperature regime].

Important geological parameters related to permafrost regions include:

1. **Thickness of the active layer**, the zone of annual freezing and thawing above permafrost, determines not only the overall strength of the ground but also many of the physical and biological processes that take place in periglacial terrains. Soil moisture and temperature, lithology, and landscape morphology exercise important controls on active layer thickness. Soil moisture and temperature depend largely on climatic factors, so that if the mean annual air temperature rises several degrees Celsius, the thickness of the active layer may change over time periods of years to decades.
2. **Frost heaving** is a basic physical process associated both with near surface winter freezing and with deeper permafrost aggradation. Frost heaving can displace buildings, roads, pipelines, drainage systems, and other structures. Many frozen soils have a much greater water content than their dry equivalents and undergo a local 10-20% expansion in soil volume during freezing. The frost heave process and the consequences of thawing are of great importance in the development of many of the unique features of cold terrains, including perennial hummocks and seasonal mounds, patterned ground, palsas, and pingos.
3. **Frost cracks** are steep fractures formed by thermal contraction in rock or frozen ground with substantial ice content. They commonly intersect to create polygonal patterns, which may

lead to the formation of wedges of ice and surficial material. The frequency of cracking is linked to the intensity of winter cold. Where climate is warming, ice-wedge casts replace ice wedges over periods of decades.

4. **Icings** are sheetlike masses of layered ice formed on the ground surface, or on river or lake ice, by freezing successive flows of water that may seep from the ground, flow from a spring or emerge from below river or lake ice through fractures. The intensity of icings in the southern portions of the permafrost zone may change annually, increasing with colder winters and lower snow cover combined with autumnal precipitation. Further north, icings increase in size but decrease in number when the climate cools, and vice-versa when it warms.
5. **Thermoerosion** refers to erosion by water combined with its thermal effect on frozen ground. Small channels can develop into gullies up to several kilometers in length, growing at rates of 10-20 m/yr, and in sandy deposits, as fast as 1 m/hr. The main climatic factors controlling the intensity of thermoerosion are snow-melt regime and summer precipitation.
6. **Thermokarst** refers to a range of features formed in areas of low relief when permafrost with excess ice thaws. These are unevenly distributed and include hummocks and mounds, water-filled depressions, “drunken” forests, mud flows on sloping ground, new fens, and other forms of thaw settlement that account for many of the geotechnical and engineering problems encountered in periglacial landscapes. Even where repeated ground freezing takes place, thermokarst features, once formed, are likely to persist.
7. Permafrost terrains are characterized by a wide range of slow downslope movements involving **creep**, such as rock glaciers and gelifluction, and by more rapid landslides and snow avalanches [see slope failure].

**Significance:** Permafrost influences natural and managed ecosystems, including forests, grasslands and rangelands, mountains and wetlands, and their hydrological systems. It is an agent of environmental change that affects ecosystems and human settlements. Permafrost may enhance further (global) climate change by the release of carbon and other greenhouse gases during thawing. Permafrost can result in serious and costly disruptions from ground subsidence, slope failure, icings, and other cryogenic processes.

**Human Influence:** The freezing and thawing of soils and surficial materials and the consequent ground changes are natural processes controlled by climatic conditions, and can be modified by human actions in and around settlements and engineering works.

Frozen ground activity (frost heave and gelifluction) is a major geologic process active in Rocky Mountain National Park. Patterned ground (e.g., stone polygons and stone stripe features) occurs in high alpine areas. These features are thought to form from frost heave and frost cracking and are extremely sensitive to human disturbance. Visitors have access to patterned ground along the “Tundra World Nature Trail.” There is limited parking in this area, which may cut down on the number of visitors who access the patterned ground. Furthermore, visitors are asked to fan out when walking across these surfaces to minimize disturbance of these features.

## <u>Glacier fluctuations</u>

**Brief Description:** Changes in glacier movement, length, and volume can exert profound effects on the surrounding environment, for example through sudden melting which can generate catastrophic floods, or surges that trigger rapid advances. Twice in the last hundred years the

Muldrow Glacier in Denali National Park and Preserve has "surged" flowing over lower stagnant ice and making a jumble of broken ice-blocks. Movement along the fault may trigger a surge.

Standard parameters include mass balance and the glacier length, which determines the position of the terminus. The location of the terminus and lateral margins of ice exerts a powerful influence on nearby physical and biological processes. Through a combination of specific balance, cumulative specific balance, accumulation area ratio, and equilibrium-line altitude, mass balance reflects the annual difference between net gains (accumulation) and losses (ablation). It may also be important to track changes in the discharge of water from the glacier as indicators of glacier hydrology. Abrupt changes may warn of impending acceleration in melting, cavitation, or destructive flooding.

**Significance:** Glaciers are highly sensitive, natural, large-scale, representative indicators of the energy balance at Earth's surface in polar regions and high altitudes. Their capacity to store water for extended periods exerts significant control on the surface water cycle. The advance and retreat of mountain glaciers creates hazards to nearby human structures and communities through avalanches, slope failure, catastrophic outburst floods from ice and moraine-dammed lakes. Notwithstanding local glacier advances, the length of mountain glaciers and their ice volume have decreased throughout the world during the past century or two, providing strong evidence for (global) climate warming, though there may also be local correlations with decreasing precipitation.

**Human Influence:** Glaciers grow or diminish in response to natural climatic fluctuations. They record annual and long-term changes and are practically undisturbed by direct human actions.

## Groundwater quality

**Brief Description**: The chemistry (quality) of groundwater reflects inputs from the atmosphere, from soil and water-rock reactions (weathering), as well as from pollutant sources such as mining, land clearance, agriculture, acid precipitation, and domestic and industrial wastes. The relatively slow movement of water through the ground means that residence times in groundwaters are generally orders of magnitude longer than in surface waters.

As in the case of surface water quality, it is difficult to simplify to a few parameters. However, in the context of geoindicators, a selection has been made of a few important first-order and second-order parameters that can be used in most circumstances to assess significant processes or trends at a time-scale of 50-100 years. The following first order indicators (in **bold**) of change are proposed, in association with a number of processes and problems, and supported by a number of second order parameters:

1. Salinity: **Cl**, SEC (specific electrical conductance), $SO_4$, Br, TDS (total dissolved solids), Mg/Ca, $\delta^{18}O$, $\delta^{2}H$, F
2. Acidity & Redox Status: **pH, $HCO_3$, Eh**, DO, Fe, As
3. Radioactivity: **$^{3}H$**, $^{36}Cl$, $^{222}Rn$
4. Agricultural Pollution: **$NO_3$**, $SO_4$, DOC (dissolved organic carbon), K/Na, P, pesticides and herbicides
5. Mining Pollution: **$SO_4$, pH**, Fe, As, other metals, F, Sr
6. Urban Pollution: **Cl, $HCO_3$, DOC**, B, hydrocarbons, organic solvents

During development and use of an aquifer, changes may occur in the natural baseline chemistry that may be beneficial or detrimental to health (e.g., increase in F, As); these should be included in monitoring programs. The quality of shallow groundwater may also be affected by landslides, fires, and other surface processes that increase or decrease infiltration or that expose or blanket rock and soil surfaces which interact with downward-moving surface water.

**Significance:** Groundwater is important for human consumption on a global scale, and changes in quality can have serious consequences. It is also important for the support of habitat and for maintaining the quality of baseflow to rivers. The chemical composition of groundwater is a measure of its suitability as a source of water for human and animal consumption, irrigation, and for industrial and other purposes. It also influences ecosystem health and function, so that it is important to detect change and early warnings of change both in natural systems and resulting from pollution.

**Human Influence:** Changes in natural baseline conditions may occur over the timescales of interest, and may be measured at an individual borehole or spring. Superimposed on these, however, are the greater impacts of human activities.

Practices in parks may influence groundwater quality. Approximately one mile south of the Canyonlands Visitor Center (Needles District) is an abandoned landfill that operated from 1966 to 1987. Hazardous substances including paint thinners, pesticides, human wastes, and oils were disposed at this landfill during operation. The soils consist of alluvial and eolian deposits (loose sandy material) of high permeability 10 to 20 feet deep; thus the potential for groundwater contamination exists in the area. The closest domestic well is 3,000 feet north of the landfill.

## Groundwater chemistry in the unsaturated zone

**Brief Description**: Water moves downwards through porous soils and sediments and, under favorable conditions, may preserve a record of weathering processes, climatic variations (in the Cl or isotopic signature), or human activities such as agriculture ($NO_3$) and acidification ($H^+$). This indicator may be considered as the output from the soil zone and may reflect the properties or change in properties of soils. Rates of downward movement are typically 0.1 to 1.0 m/yr, and a record of individual events (resolution 1-20+ years) may be preserved over a scale of decades or centuries [see groundwater quality; soil quality]. In contrast, records collected over periods of years are needed to establish trends from the monitoring of rivers and streams or groundwater discharge [see groundwater quality; surface water quality]. The unsaturated zone is also an important buffering zone for attenuation of acidity, metal content, and some other harmful substances.

**Significance:** Changes in recharge rates have a direct relationship to water resource availability. The unsaturated zone may store and transmit pollutants, the release of which may have a sudden adverse impact on groundwater quality.

**Human Influence:** Depending on land use, the unsaturated zone beneath a site may record the effects of human activities such as agriculture and industrial activity, or regional problems such as acidic deposition.

## Groundwater level

**Brief Description**:  Groundwater is replenished from precipitation and from surface water, but the rate of abstraction (withdrawal by humans) may exceed the rate of natural recharge, leading to reduction of the resource. Some aquifers, especially in arid and semi-arid regions, contain paleowaters (fossil groundwater) stored from earlier periods of wetter climate; the reduction of these reserves is comparable to "mining." In alluvial plains, reduction in streamflow reduces the rate of natural recharge to aquifers. Measurement on a regular basis of water levels in wells and boreholes or of spring discharge provides the simplest indicator of changes in groundwater resources. However, springs may be perennial, intermittent, or periodic, and their discharge may depend on changes in climate, tides, and local underground conditions such as changes in rock stresses.

**Significance:** The availability of clean water is of fundamental importance to the sustainability of life. It is essential to know how long the resource will last and to determine the present recharge: groundwater mining is a terminal condition.

**Human Influence:** There are natural changes in groundwater levels because of climate change (drought, pluvial episodes), but the main changes are due to human abstraction. In many places artificial recharge of aquifers is accomplished deliberately by pumping or as an indirect result of irrigation.

The majority of available fresh water in Cape Cod National Seashore is groundwater. On the lower Cape, all groundwater has local precipitation as its source. The groundwater resource directly supports most of the lower Cape's surface water—ponds, streams, and fresh water wetlands. The human populations of the lower Cape are also entirely dependent on the groundwater for private and municipal water supply.

There are three primary groundwater withdrawal concerns facing Cape Cod National Seashore as development continues and the demand for new private and public water wells increases.  First, excessive groundwater withdrawals can lower the local water table, potentially depleting pond, wetland, and vernal pool water levels.  Second, large-scale, sustained pumping can decrease aquifer discharge, impacting streams and estuaries.  Finally, under extreme cases, the groundwater volume may be depleted to a point where salt water intrudes and contaminates the fresh groundwater.

**<u>Karst activity</u>**

**Brief Description:** Karst is a type of landscape found on carbonate rocks (limestone, dolomite, marble) or evaporites (gypsum, anhydrite, rock salt) and is typified by a wide range of closed surface depressions, well-developed underground drainage system, and a paucity of surface streams. The highly varied interactions among chemical, physical, and biological processes have a broad range of geological effects including dissolution, precipitation, sedimentation, and ground subsidence. Diagnostic features such as sinkholes (dolines), sinking streams, caves, and large springs are the result of the solutional action of circulating groundwater, which may exit to entrenched effluent streams. Most of this underground water moves by laminar flow within narrow fissures, which may become enlarged above, at, or below the water table to form subsurface caves, in which the flow may become turbulent. Caves contain a variety of dissolution features, sediments, and speleothems (deposits with various forms and mineralogy, chiefly calcite), all of which may preserve a record of the geological and climatic history of the area. Karst deposits and landforms may persist for extraordinarily long times in relict caves and paleokarst. Karst can be either a sink or a source of $CO_2$, for the karst process is part of the global carbon cycle in which carbon is exchanged between the atmosphere, surface and underground water and carbonate minerals. Dissolution of carbonates, which is enhanced by the presence of acids in water, ties up carbon derived from the rock and from dissolved $CO_2$ as aqueous $HCO_3$-. Deposition of dissolved carbonate minerals is accompanied—and usually triggered—by release of some of the carbon as $CO_2$. In many karst locations, $CO_2$ emission is associated with the deposition of calcareous sinter (tufa, travertine) at the outlet of cold or warm springs.

Though most abundant in humid regions, karst can also be found in arid terrains where $H_2S$ in groundwater, rising from reducing zones at depth, oxidizes to produce sulphuric acid, which can form large caves, such as the Carlsbad Caverns of New Mexico. Similar processes also operate in humid regions but tend to be masked by the $CO_2$ reaction. Sulphates and rock salt are rarely exposed in humid climates. They are susceptible to rapid dissolution during periodic rains where they are at the surface in drier terrains.

**Significance:** Karst systems are sensitive to many environmental factors. The presence and growth of caves may cause short-term problems, including bedrock collapse, disparities in well yields, poor groundwater quality because of lack of filtering action, instability of overlying soils, and difficulty in designing effective monitoring systems around waste facilities. Instability of karst surfaces causes damage to roads, buildings, and other structures. Radon levels in karst groundwater tend to be high in some regions, and underground solution conduits can distribute radon unevenly throughout a particular area.

**Human Influence:** Natural karst processes can be influenced by human activities such as land-use modification (e.g., deforestation), waste disposal, and opening or blocking of cave entrances, all of which can substantially affect sedimentation, speleothem deposition, and groundwater quality over the short term. Although most sinkhole collapse is triggered by high discharge of underground streams, lowering of water tables by overpumping in areas underlain by thick soils or weak rocks can induce ground failure and collapse into subsurface voids.

## Lake levels and salinity

**Brief Description**: Lakes are dynamic systems that are sensitive to local climate and to land-use changes in the surrounding landscape [see shoreline position]. Some lakes receive their water mainly from precipitation, some are dominated by drainage runoff, and others are controlled by groundwater systems. On a time scale ranging from days to millennia, the areal extent and depth of water in lakes are indicators of changes in climatic parameters such as precipitation, radiation, temperature, and wind speed. Lake level fluctuations vary with the water balance of the lake and its catchment, and may, in certain cases, reflect changes in shallow groundwater resources.

Especially useful as climatic indicators are lakes without outlets (endorheic). In arid and semi-arid areas, the levels and areas of lakes with outflows are also highly sensitive to weather. Where not directly affected by human actions, lake level fluctuations are excellent indicators of drought conditions. Ephemerally- or seasonally-flooded lake basins (playas) are dynamic landforms, the physical character and chemical properties of which reflect local hydrologic changes, and which react sensitively to short-term climate changes (e.g., rate of evaporation). Fluctuations in lake water salinity also provide an indication of changes in conditions at the surface (climate, inflow/outflow relations) and in shallow groundwater [see sediment sequence and composition; surface water quality].

**Significance:** The history of fluctuations in lake levels provides a detailed record of climate changes on a scale of a decade to a million years. Lakes can also be valuable indicators of near-surface groundwater conditions.

**Human Influences:** Lake levels can be influenced by human-induced climate change, and by engineering works, such as dams and channels. Less drastic actions can also influence lake levels, for example, North Bar Lake in Sleeping Bear Dunes National Seashore, is an embayment lake that is being “loved to death.” Historically, the lake was directly connected to Lake Michigan by an outlet channel. Heavy foot traffic has removed natural vegetation and destabilized the dunes near the lake. Increased sand transport from the dunes has filled in the outlet channel closing off the embayment lake, and, as a result, the embayment lake has lost its natural lake level fluctuation.

**Relative sea level**

**Brief Description:** The position and height of sea relative to the land (relative sea level - RSL) determines the location of the shoreline [see shoreline position]. Though global fluctuations in sea level may result from the growth and melting of continental glaciers, and large-scale changes in the configuration of continental margins and ocean floors, there are many regional processes that result in rise or fall of RSL that affect one coastline and not another. These include: thermal expansion of ocean waters, changes in meltwater load, crustal rebound from glaciation, uplift or subsidence in coastal areas related to various tectonic processes (e.g., seismic disturbance and volcanic action), fluid withdrawal, and sediment deposition and compaction. RSL variations may also result from geodetic changes such as fluctuations in the angular velocity of Earth or polar drift.

**Significance:** Changes in RSL may alter the position and morphology of coastlines, causing coastal flooding, waterlogging of soils, and a loss or gain of land. They may also create or destroy coastal wetlands and salt marshes, inundate coastal settlements, and induce salt-water intrusion into aquifers, leading to salinization of groundwater. Coastal ecosystems are bound to be affected, for example, by increased salt stress on plants. A changing RSL may also have profound effects on coastal structures and communities. Low-lying coastal and island states are particularly susceptible to sea-level rise.

**Human Influences:** Human actions including drainage of wetlands, withdrawal of groundwater (which eventually flows to the sea), and deforestation (which reduces terrestrial water storage capacity) may contribute to global rise in sea level. Human-induced climate change is also of obvious importance. Large engineering works, such as river channeling or dam construction, that influence sediment delivery and deposition in deltaic areas may cause local changes.

A big question in Cape Cod National Seashore is whether the marshes can keep up with sea-level rise. Cape Cod’s fresh groundwater rests on seawater and necessarily rises along with sea level; therefore, the diked Pamet marsh, for example, continues to rise along with groundwater levels, but in a way that is very different from the way salt marshes normally grow. Salt marshes typically keep pace with sea-level-rise largely through the accumulation of inorganic sediment, i.e., sand, silt, and clay. The diked upper Pamet has been denied this sediment supply for over 100 years. In the meantime, any accretion has been through the production of organic matter.

Similarly, the engineering of the Mississippi River over the past 200 years has cut off sediment from nourishing and accreting the marshes at Jean Lafitte National Historical Park and Preserve (New Orleans, Louisiana), such that as the marshes subside, no new sediment is available to maintain marsh elevation.

## Sediment sequence and composition

**Brief Description:** Lakes, wetlands, streams (and overbanks), estuaries, reservoirs, fjords, shallow coastal seas, and other bodies of marine or fresh water commonly accumulate deposits derived from bedrocks, soils, and organic remains within the drainage basin, though fine particles can also be blown in by winds from distant natural, urban, and industrial sources. These aquatic deposits may preserve a record of past or on-going environmental processes and components, both natural and human-induced, including soil erosion [see soil and sediment erosion; wetlands extent, structure, and hydrology], air-transported particulates [see dust storm magnitude, duration, and frequency], solute transport, and landsliding [see slope failure]. Some of these bodies of water are dynamic and sensitive systems whose sedimentary deposits preserve in their chemical, physical, and biological composition a chronologically ordered and resolvable record of physical and chemical changes through their mineralogy, structure, and geochemistry [see surface water quality]. Of particular value in determining long-term data on water chemistry are the remains of aquatic organisms, which can be correlated with various environmental parameters. In addition, fossil pollen, spores, and seeds reflect past terrestrial and aquatic vegetation. Sediment deposits can, thus, provide an indication of the degree and nature of impact of past events on the system, and a baseline for comparison with contemporary environmental change. Some lakes (and reservoirs) are open systems characterized by relatively stable shorelines and a limited residence time for solutes; others are closed (endorheic) and/or ephemeral (playas).

**Significance:** The chemical, physical, and biological character of aquatic sediments can provide a finely resolvable record of environmental change, in which natural events may be clearly distinguishable from human inputs.

**Human Influence:** Sediment deposition is a natural process that can be strongly influenced by human activities (e.g., land clearing, agriculture, deforestation, acidification, eutrophication, industrial pollution) within the drainage basin or sediment catchment.

George Washington Birthplace National Monument, specifically the Popes Creek watershed, serves as a reference system for environmental studies in the Chesapeake Bay region. Sediment sequences have recorded the history of farming and development beginning in colonial times. The farming activities and development in the Popes Creek watershed occurred at a much lower level than similar coastal plain watersheds in the area. The sediment sequence in Popes Creek watershed, which is geologically similar to other systems in the Chesapeake Bay region, has provided baseline information for the studies that examine the affects of human activities on natural processes.

## Seismicity

**Brief Description:** Crustal movements along strike-slip, normal, and thrust faults cause shallow-focus earthquakes (those with sources within a few tens of kilometers of Earth's surface), though they can also be human-induced. They can result in marked temporary or permanent changes in the landscape, depending on the magnitude of the earthquake, the location of its epicenter, and local soil and rock conditions [see surface displacement]. Deep-focus earthquakes (below about 70 km), unless of the highest magnitude, are unlikely to have serious surface manifestations.

To avoid, reduce, or warn of environmental impacts, it is necessary to know the size, location, and frequency of seismic events. These parameters can identify active faults and the sense of motion along them. Also of great importance is the spatial pattern of seismicity, including the presence of seismic gaps, and the relationship to known faults and active volcanoes. At least three, and generally many more, monitoring sites are required to determine the necessary parameters.

Seismic observations constitute one of the oldest forms of systematic monitoring of earth processes. There are now in operation many national, regional, and international seismic networks, which provide information about the location, size, and motion of earthquakes anywhere in the world. However, shallow-focus tremors of lower magnitude, may not be detected by these means, and must be monitored more closely, on a local basis. Seismic hazard maps can be constructed to identify areas at varying risk from earthquake damage.

**Significance:** Earthquakes constitute one of the greatest natural hazards to human society. Surface effects include uplift or subsidence, surface faulting, landslides and debris flows, liquefaction, ground shaking, and tsunamis ("tidal" waves caused by undersea tremors). Damage to buildings, roads, sewers, gas and water lines, power and telephone systems, and other built structures commonly occur.

**Human Influence:** Earthquakes are predominantly natural events. However, shallow-focus seismic tremors can be induced by human actions that change near-surface rock stresses or fluid pressures. These actions include: extracting or injecting water, gas, petroleum, or waste fluids into the ground for storage or for secondary hydrocarbon recovery; mining or quarrying activities; and loading the surface with large water bodies (reservoirs). Underground explosions, particularly for nuclear testing, can also generate seismic events. Deep injection of water at the Potash Mine on the boundary of Canyonlands National Park is known to induce earthquakes.

## Shoreline position

**Brief Description**: The position of the shoreline along ocean coasts and around inland waters (lakes) varies over a broad spectrum of time scales in response to shoreline erosion (retreat) or accretion (advance), changes in water level, and land uplift or subsidence [see relative sea level; surface displacement]. Long-term trends in shoreline position may be masked in the short term by variations over periods of days to years, related, for example, to individual storms, changes in storminess, and El Niño/Southern Oscillation effects. Shoreline position reflects the coastal sediment budget, and changes may indicate natural or human-induced effects alongshore or in nearby river catchments. The detailed shape and sedimentary character of a beach (e.g., beach slope, cusp dimensions, bar position and morphology, barrier crest and berm elevation, sediment size and shape) are highly sensitive to oceanographic forcing, including deep-water wave energy, nearshore wave transformation, wave setup, storm surge, tides, and nearshore circulation: morphodynamic adjustments and feedbacks are common. Qualitative assessments of shoreline morphology can be used as a proxy for shore-zone processes, partially substituting for more quantitative measures of shoreline change where these are not available.

**Significance:** Changes in the position of the shoreline affect transportation routes, coastal installations, communities, and ecosystems. The effects of shoreline erosion on coastal communities and structures can be drastic and costly. It is of paramount importance for coastal settlements to know if local shorelines are advancing, retreating, or stable.

**Human Influence:** Erosion and sediment accretion are on-going natural processes along all coasts. Human activities (e.g., dredging, beach mining, river modification, installation of protective structures such as breakwaters, removal of backshore vegetation, reclamation of nearshore areas) can profoundly alter shoreline processes, position, and morphology, in particular by affecting the sediment supply.

In Fire Island National Seashore, a groin was installed to protect a water tower at Ocean Beach from erosion by currents, tides, and waves. The effect of the groin was to cause accelerated erosion downshore. This retreat of shoreline continued to migrate downshore through the barrier island system at a rate of one kilometer per year, holding the shape of an eight-foot scarp in the sand. Rough calculations estimate human-induced changes to the shoreline position amount to approximately two meters of beach recession in the last 45-50 years.

## Slope failure

**Brief Description:** There are many ways in which slopes may fail, depending on the angle of slope, the water content, the type of earth material involved, and local environmental factors such as ground temperature. Slope failure may take place suddenly and catastrophically or may be more gradual. Slope failure results in landslides, debris and snow avalanches, lahars, rock falls, flows (debris, quick clay, loess, and dry or wet sand and silt), slides (debris, rock), topples, slumps (rock, earth), and creep.

Special conditions and processes exist in permafrost terrains. Landslides and mudflows of permafrost regions are mobilized and shaped by the freezing and thawing of pore water in the active layer, the base of which acts as a shear discontinuity. Failure here can occur on slopes as low as 1º. Gelifluction (a form of solifluction, the slow downslope movement of waterlogged soil and surficial debris) is the regular downslope flow or creep of seasonally frozen and thawed soils. Gentle to medium slopes with blankets of loose rock fragments overlying frozen ground may be subject to mass movements such as rock glaciers and rock streams or kurums [see frozen ground activity]. Catastrophic slope failure here can expose new frozen ground, setting off renewed mass wasting.

Three parameters are particularly important for monitoring all kinds of mass movements:

1. **Ground cracks** are the surface manifestation of a variety of mass movements. In plan, they are commonly concentric or parallel, and have widths of a few centimeters and lengths of several meters, which distinguishes them from the much shorter desiccation cracks [see

desert surface crusts and fissures]. The formation of cracks and any increase in their rate of widening is a common measure of impending slope failure.
2. The appearance of and increases in **ground subsidence or upheaval** is also a good measure of impending failure.
3. The **area of slope failure** is a measure of the extent of landsliding in any region. Changes over time may both reflect significant environmental stresses (e.g., deforestation, weather extremes) and provide important clues about landscape and ecosystem degradation.

Climate change may accelerate or slow the natural rate of slope failure, through changes in precipitation or in the vegetation cover that binds loose slope materials. Wildfires can also promote mass movements by destroying tree cover. However, it is difficult to generalize where information is lacking on the present distribution and significance of landslides because many parameters, in addition to climate change, contribute to slope stability.

**Significance:** Slope failure causes death and property damage. Damage to ecosystems has not generally been documented, but landslides may destroy habitats, for example by blocking streams and denuding slopes.

**Human Influence:** Slope failure is a natural process that may be induced, accelerated, or retarded by human actions. Human influences include:

1. **Removal of lateral support** through human actions such as cutting slopes for roads and other structures, quarrying, removal of retaining walls, and lowering of reservoirs.
2. **Adding weight** to slopes by human actions such as landfills, stockpiles of ore or rock, waste piles, construction of heavy building and other structures, fill, and retaining walls.
3. **Vibrations** from explosions, machinery, road and air traffic.
4. **Decrease of underlying support** through mining.
5. **Lubricating slope materials** with water leaking from pipelines, sewers, canals, and reservoirs.

The Grand Ditch in Rocky Mountain National Park is a 16.2-mile aqueduct that diverts water from the West Slope streams to farms, ranches, towns, and cities on the eastern plains. Completed in 1936, it is one of the earliest transmountain diversions in Colorado. The Grand Ditch, which is cut into the mid- to upper slopes of the Never Summer Mountains, causes landslides in the upper Colorado River from undercutting the hillslope. Landslide material deposited in the Grand Ditch is side cast by bulldozers downslope when the ditch is cleaned annually.

**<u>Soil and sediment erosion</u>**

**Brief Description:** Erosion—the detachment of particles of soil and surficial sediments and rocks—occurs by hydrological (fluvial) processes of sheet erosion, rilling and gully erosion, and through mass wasting and the action of wind [see sediment geochemistry and stratigraphy; stream sediment storage and load; wind erosion]. Erosion, both fluvial and eolian (wind), is generally greatest in arid and semi-arid regions, where soil is poorly developed and vegetation provides relatively little protection. Where land use causes soil disturbance, erosion may increase greatly above natural rates. In uplands, the rate of soil and sediment erosion approaches that of denudation (the lowering of Earth's surface by erosional processes). In many areas, however, the storage of eroded sediment on hillslopes of lower inclination, in bottomlands, and in lakes and reservoirs, leads to rates of stream sediment transport much lower than the rate of denudation.

When runoff occurs, less water enters the ground, thus reducing plant productivity. Soil erosion also reduces the levels of the basic plant nutrients needed for growth, and decreases the diversity and abundance of soil organisms. Stream sediment degrades water supplies for municipal and industrial use, and provides an important transporting medium for a wide range of chemical pollutants that are readily sorbed on sediment surfaces. Increased turbidity of coastal waters due to sediment load may adversely affect organisms such as benthic algae, corals, and fish.

**Significance:** Soil erosion is an important social and economic problem and an essential factor in assessing ecosystem health and function. Estimates of erosion are essential to issues of land and water management, including sediment transport and storage in lowlands, reservoirs, estuaries, and irrigation and hydropower systems.

**Human Influences:** Erosion is a fundamental and complex natural process that is strongly modified (generally increased) by human activities such as land clearance, agriculture (ploughing, irrigation, grazing), forestry, construction, surface mining, and urbanization. Humans induce both water and wind erosion, which may result in chemical and physical deterioration of soil [see soil quality].

Within Sleeping Bear Dunes National Seashore, there are 11 major gravel and sand extraction pits or topsoil mining sites. The largest site is a 65-acre topsoil-mining site (STAN site); another site covers 40 acres on Scenic Drive.

**Soil quality**

**Brief Description:** Soils vary greatly in time and space. Over time-scales relevant to geoindicators, they have both stable characteristics (e.g., mineralogical composition and relative proportions of sand, silt, and clay) and those that respond rapidly to changing environmental conditions (e.g., ground freezing). The latter characteristics include soil moisture and soil microbiota (e.g., nematodes, microbes), which are essential to fluxes of plant nutrients and greenhouse gases. The soils of boreal regions are estimated to hold the equivalent of some 60% of the current atmospheric carbon: long-term warming is expected to increase decomposition and drying, thus potentially releasing huge volumes of methane and $CO_2$.

Most soils resist short-term climate change, but some may undergo irreversible change such as lateritic hardening and densification, podsolization, or large-scale erosion. Soil properties and climatic variables such as mean annual rainfall and temperature can be related by mathematical functions known as climofunctions.

Chemical degradation takes place because of depletion of soluble elements through rainwater leaching, overcropping and overgrazing, or because of the accumulation of salts precipitated from rising groundwater or irrigation schemes. It may also be caused by sewage containing toxic metals, precipitation of acidic and other airborne contaminants, as well as by persistent use of fertilizers and pesticides. A widespread problem is the retention in the soil organic matter and clay minerals of potentially toxic metals and radionuclides (e.g., Cu, Hg, Pb, Zn, $^{226}Ra$, $^{238}U$). These and other chemical components may be catastrophically released as what are commonly referred to as “chemical time bombs” where the pH of the soil is decreased by acidification or where other environmental disturbances (e.g., erosion, drought, land use change) intervene. Soils also act as a primary barrier against the migration of organic contaminants into groundwater. Key indicators are pH, organic matter content, sodium absorption ratio, cation exchange capacity, and cation saturation.

Physical degradation results from land clearing, and erosion and compaction by machinery. Soil structure may be altered so that infiltration capacity and porosity are decreased, and bulk density and resistance to root penetration are increased. Such soils have impeded drainage and are quickly saturated: the resultant runoff can cause accelerated erosion and transport of pollutants such as pesticides [see soil and sediment erosion]. The key soil indicators are texture (especially clay content), bulk density, aggregate stability and size distribution, and water-holding capacity.

**Significance:** As one of Earth’s most vital ecosystems, soil is essential for the continued existence of life on the planet. As sources, stores, and transformers of plant nutrients, soils have a major influence on terrestrial ecosystems. Soils continuously recycle plant and animal remains, and they are major support systems for human life, determining the agricultural production capacity of the land. Soils buffer and filter pollutants; they store moisture and nutrients; and they are important sources and sinks for $CO_2$, methane, and nitrous oxides. Soils are a key system for the hydrological cycle [see groundwater chemistry in the unsaturated zone]. Soils also provide an archive of past climatic conditions and human influences.

**Human Influences:** Soils may be degraded or enhanced by both natural processes and human activities. Human activities influence soil properties by causing increases in bulk density from agricultural tillage and road operations and in acidification from inorganic fertilizers and acid rain. Soil degradation is one of the largest threats to environmental sustainability.

## Streamflow

**Brief Description**: Streamflow varies with the volume of water, precipitation, surface temperature, and other climatic factors. For most streams (rivers), the highest water discharge is found close to the sea, but in arid regions discharge decreases naturally downstream. Land use in drainage basins also strongly affects streamflow. Major streamflow regimes include glacial, nival, dry tropical, monsoon, equatorial, and desert. Reversals in streamflow, in conjunction with indirect methods of paleoflood studies and paleohydrology, yield long-term indicators of changes in discharge that are valuable for responses to flooding, estimating long-term trends in water and sediment discharges, and for distinguishing possible long-term climate change.

**Significance:** Streamflow directly reflects climatic variation. Stream systems play a key role in the regulation and maintenance of biodiversity. Changes in streams and streamflow are indicators of changes in basin dynamics and land use.

**Human Influences:** Natural variations in streamflow predominate, but they can be strongly modified by human actions, such as dams and reservoirs, irrigation, and diversion for use outside the watershed.

Only two perennial streams, Leach and Little Cottonwood Creeks, are present in Craters of the Moon National Monument. These streams drain the Pioneer Mountains in the north end of the park. Diversion of streamflow in Little Cottonwood Creek began in the 1930s for park operations. Water demand was low until the late 1950s when the visitor center complex was built. It is estimated that peak consumption occurred in the late 1960s when over 50% of the streamflow was diverted out of the channel. At present (2000) this use has decreased to approximately 30% due to the reduction in the area of irrigated lawns.

**Stream channel morphology**

**Brief Description:** Alluvial streams (rivers) are dynamic landforms subject to rapid change in channel shape and flow pattern. Water and sediment discharges determine the dimensions of a stream channel (width, depth, and meander wavelength and gradient). Dimensionless characteristics of stream channels and types of pattern (braided, meandering, straight) and sinuosity are significantly affected by changes in flow rate and sediment discharge, and by the type of sediment load in terms of the ratio of suspended to bed load [see stream sediment storage and load]. Dramatic changes in stream bank erosion within a short time period indicate changes in sediment discharge.

**Significance:** Channel dimensions reflect magnitude of water and sediment discharges. In the absence of hydrologic and streamflow records, an understanding of stream morphology can help delineate environmental changes of many kinds. Changes in stream pattern, which can be very rapid in arid and semi-arid areas, place significant limits on land use, such as on islands in braided streams and meander plains, or along banks undergoing erosion.

**Human Influences:** Significant changes in stream dimensions, discharge, and pattern may reflect human influences such as water diversion and increased sediment loads resulting from land clearance, farming, or forest harvesting. Such variations are also responsive to climatic fluctuations and tectonics.

Only two perennial streams, Leach and Little Cottonwood Creeks, are present in Craters of the Moon National Monument. There is evidence that the lower portion of Little Cottonwood Creek was historically diverted out of its natural channel. The creek makes a 90º bend, and a line of dead cottonwood trees and a ground depression indicate where the channel used to be. The channel morphology of Leach Creek has also been altered. There are old impoundments or control structures in the upper portion of the creek. A dry channel in the lower portion indicates that the creek was historically diverted out of its natural channel. Both creeks continue to be diverted out of their original channels (2000).

**Stream sediment storage and load**

**Brief Description:** The load (discharge, tonnes/year) or yield (tonnes/km$^2$/year) of sediment (in suspension and as bed load of sand and gravel) through stream (river) channels reflects upland erosion within the drainage basin and change in storage of sediment in alluvial bottomlands [see soil and sediment erosion]. In turn, climate, vegetation, soil and rock type, relief and slope, and human activities such as timber harvesting, agriculture, and urbanization influence stream sediment storage and load. Much of the sediment eroded from upland areas is deposited (stored) on lower hillslopes, in bottomlands, and in lakes and reservoirs. Flash floods in ephemeral desert streams may transport very large sediment loads, accounting for unforeseen sedimentation problems in dryland stream reservoirs.

**Significance:** Sediment load determines channel shape and pattern [see stream channel morphology]. Changes in sediment yield reflect changes in basin conditions, including climate, soils, erosion rates, vegetation, topography, and land use. Fluctuations in sediment discharge affect a great many terrestrial and coastal processes, including ecosystem responses, because nutrients are transported together with the sediment load. For example, to reproduce effectively, salmon and trout need gravel stream beds for spawning and egg survival; silt and clay deposits formed by flooding or excessive erosion can destroy these spawning beds. Stream deposits also represent huge potential sinks for, and sources of, contaminants.

**Human Influences:** Stream sediment storage and load is influenced strongly by human actions, such as in the construction of dams and levees, forest harvesting, and farming in drainage basins.

**Subsurface temperature regime**

**Brief Description:** Temperatures in boreholes a few hundred meters deep can be an important source of information on recent climatic changes because the normal upward heat flow from Earth's crust and interior is perturbed by the downward propagation of heat from the surface. As temperature fluctuations are transmitted downward, they become progressively smaller, with shorter-period variations attenuating more rapidly than longer ones. Although seasonal oscillations may be undetectable below about 15 m, century-long temperature records may be observed to depths of 150 m or so. Bedrocks thus selectively retain the long-term trends required for reconstructing climate change.

The surface temperature is strongly affected by local factors such as thickness and duration of snow cover, type of vegetation, properties of organic soil layers, depth to the water table, and topography. It influences, in turn, a wide range of ground and surface processes, particularly in the near-surface portions of permafrost [see frozen ground activity]. Below the active layer, where ground temperature fluctuates seasonally as thawing and freezing take place, long-term temperature variations may be recorded. Here, repeated measurements of soil temperature at fixed locations can reveal both the long-term dynamics of seasonally frozen ground and long-term climatic fluctuations, though the conversion of ground temperature to climate history is a complex matter.

**Significance:** The thermal regime of soils and bedrocks exercises an important control on the soil ecosystem, on near-surface chemical reactions (e.g., involving groundwater), and on the ability of these materials to sequester or release greenhouse gases. It may affect the type, productivity, and decay of plants; the availability and retention of water; the rate of nutrient cycling; and the activities of soil microfauna. It is also of major importance as an archive of climate change, indicating changes in surface temperature over periods of up to 2-3 centuries, for example in regions without a record of past surface temperatures. In permafrost, the ground temperature controls the mechanical properties of the soils, especially during the freeze-thaw transition in the active layer.

**Human Influence:** The subsurface temperature regime reflects both the natural geothermal flux from Earth's interior and the surface temperature. The latter can be modified by human actions, such as land clearing, wetland destruction, agriculture, deforestation, flooding of land for reservoirs, or development of large settlements that give rise to a "heat island" effect.

## Surface displacement

**Brief Description:** Earth's surface is subject to small but significant displacements (uplift, subsidence, lateral movement, rotation, distortion, dilation) that affect elevation and horizontal position. These movements result from active tectonic processes, collapse into underground cavities, or the compaction of surficial materials. Sudden movements may be caused by faulting associated with earthquakes [see seismicity], and from the collapse of rock or sediment into natural holes in soluble rocks (e.g., salt, gypsum, limestone) [see karst activity], or into cavities produced by mining of near-surface rocks (especially coal) and solution-mining of salt. Slower local subsidence may also be induced by: fluid withdrawal (gas, oil, groundwater, geothermal fluids); densification or loss of mass in peat being developed for agriculture; drainage of surface waters from wetlands, which can cause oxidation, erosion, and compaction of unconsolidated soils and sediments [see wetlands extent, structure, and hydrology]; and filtration of surface water through porous sediments such as loess. On a much larger scale, the land surface elevation responds slowly to plate movements, compaction of sedimentary basins, and glacial rebound.

Fissures and faults can develop suddenly during earthquakes and as a result of volcanic processes and landsliding, or more slowly as a result of differential compaction during subsidence. In arid and semi-arid terrains, fissures up to several kilometers long and a few centimeters wide may be rapidly eroded by surface run-off to gullies.

**Significance:** Most surface displacements have but minor effects on landscapes and ecosystems. However, there are exceptions, such as where drainage channels are suddenly displaced by faults, or where seismically-induced uplift raises intertidal ecosystems above sea-level. Moreover, extraction of fluids beneath urban areas can induce land subsidence and cause flooding, especially of coastal communities near sea-level. Subsidence damages buildings, foundations, and other built structures.

**Human Influence:** Surface displacements are natural phenomena associated with plate movements, glacial rebound, and faulting, but human activities such as extraction of groundwater, oil, and gas can also induce surface subsidence.

In Cape Cod National Seashore, surface displacement is linked to other geoindicators: relative sea level and wetlands. Ditching and diking of formerly tidal wetlands have caused significant subsidence within the Seashore. The subsidence is significant not with respect to aerial extent, but to the sensitivity of habitats affected and the challenge subsidence poses to restoration efforts.

## Surface water quality

**Brief Description**: The quality of surface water in rivers and streams, lakes, ponds, and wetlands is determined by interactions with soil, transported solids (organics, sediments), rocks, groundwater, and the atmosphere. It may also be significantly affected by agricultural, industrial, mineral and energy extraction, urbanization, and other human actions, as well as by atmospheric inputs. The bulk of the solutes in surface waters, however, are derived from soils and groundwater baseflow where the influence of water-rock interactions is important [see groundwater quality; karst activity; soil and sediment erosion; soil quality; streamflow; wetlands extent, structure, and hydrology].

**Significance:** Clean water is essential for the survival of all forms of life. Most is used for irrigation, with lesser amounts for municipal, industrial, and recreational purposes; only 6% of all water is used for domestic consumption. Pathogens such as bacteria, viruses, and parasites are among the world's most dangerous environmental pollutants and cause water-borne diseases. Water quality data are essential for the implementation of responsible water quality regulations, for characterizing and remediating contamination, and for the protection of the health of humans and other organisms.

**Human Influence:** The water quality of a lake, reservoir, or river can vary in space and time according to natural morphological, hydrological, chemical, biological, and sedimentological processes (e.g., changes of erosion rates). Pollution of natural bodies of surface water is widespread because of human activities, such as disposal of sewage and industrial wastes, land clearance, deforestation, use of pesticides, mining, and hydroelectric developments.

Trespass cattle at springs in Arches National Park raise a concern regarding maintenance of good water quality. Impacts include trampled soil and vegetation, increased sedimentation, and elevated levels of fecal contamination.

Herbicides to decrease the number of tamarisk stands may cause water quality problems associated with streams and springs in Arches National Park, Canyonlands National Park, and Natural Bridges National Monument.

**Volcanic unrest**

**Brief Description:** Eruptions are almost always preceded and accompanied by volcanic unrest, indicated by variations in the geophysical and geochemical state of the volcanic system. Such geoindicators commonly include changes in seismicity, ground deformation, nature and emission rate of volcanic gases, fumarole and/or ground temperature, and gravity and magnetic fields. Volcanic unrest can also be expressed by changes in temperature, composition, and level of crater lakes, and by anomalous melting or volume changes of glaciers and snow fields on volcanoes. When combined with geological mapping and dating studies to reconstruct comprehensive eruptive histories of high-risk volcanoes, these geoindicators can help to reduce eruption-related hazards to life and property. However, not all volcanic unrest culminates in eruptions; in many cases the unrest results in a failed eruption in which the rising magma does not breach the surface and erupt.

**Significance:** Natural hazards associated with eruptions pose a significant threat to human and animal populations. Before 1900, two indirect hazards—volcanogenic tsunamis and post-eruption disease and starvation—accounted for most of the eruption-associated human fatalities. In the 20th century, however, direct hazards related to explosive eruptions (e.g., pyroclastic flows and surges, debris flows, mudflows) were the most deadly hazards.

**Human Influence:** None. Volcanism is a natural process that has operated since the formation of Earth. Although a few attempts have been made to divert lava flows, humans have had no influence whatsoever on the underlying causes of volcanism.

## Wetlands extent, structure, and hydrology

**Brief Description**: Wetlands are complex and sensitive ecosystems, characterized by a water table at or near the land surface for some part of the year, by soil conditions that differ from adjacent uplands, and by vegetation adapted to wet conditions. Wetlands are usually classified on the basis of their morphology and vegetation and, to a lesser extent, their hydrology. Though definitions vary, the following types are widely recognized: coastal salt and freshwater marshes; swamps (mangrove, shrub, and wooded); wet grasslands, meadows, and prairies; and peatlands (landforms in which organic sediments have accumulated to depths in excess of 30-50 cm), including mires, moors, muskeg, bogs, and fens.

The areal extent, distribution, and surface and internal structures of a wetland can be altered by many processes, such as organic and inorganic sediment deposition and erosion, paludification (lateral spread), terrestrialization (colonization of open water by wetland plant communities), and changing hydrology. In the case of coastal wetlands, saltwater intrusion and changes in sea level can also be important [see relative sea level; shoreline position].

Hydrological relationships play a key role in wetland ecosystem processes, and in determining structure and growth. Different wetlands have a characteristic hydroperiod, or seasonal pattern of water levels, that defines the rise and fall of surface and subsurface water. An important geoindicator is the water budget of a wetland, which links inputs from groundwater, runoff, precipitation, and physical forces (wind, tides) with outputs from drainage, recharge, evaporation, and transpiration. Annual or seasonal changes in the range of water levels affect visible surface biota, decay processes, accumulation rates, and gas emissions. Such changes can occur in response to a range of external factors, such as fluctuations in water source (river diversions, groundwater pumping), climate, or land use (forest clearing). Waters flowing out of wetlands are chemically distinct from inflow waters, because a range of physical and chemical reactions take place as water passes through organic materials, such as peat, causing some elements (e.g., heavy metals) to be sequestered and others (e.g., DOC, humic acids) to be mobilized. A baseline of wetland conditions may be established through a paleoecological study to investigate whether a present-day wetland is stable or actively evolving, and if so in what direction and at what rate.

**Significance:** Wetlands are areas of high biological productivity and diversity. They provide important sites for wildlife habitat and human recreation. Wetlands mediate large- and small-scale environmental processes by altering downstream catchments. The dissolved carbon burden of wetlands may affect downstream waters, for example by acid drainage. Wetlands can affect local hydrology by acting as a filter, sequestering and storing heavy metals and other pollutants, such as Hg, and serving as flood buffers and, in coastal zones, as storm defenses and erosion controls.

Wetlands can act as carbon sinks, storing organic carbon in waterlogged sediments. Even slowly growing peatlands may sequester carbon at between 0.5 and 0.7 tonnes/ha/yr. Wetlands can also be a carbon source, when it is released via degassing during decay processes, or after drainage and cutting, as a result of oxidation or burning.

**Human Influence:** Wetlands develop naturally in response to morphological and hydrological features of the landscape. Their evolution can be affected by external factors such as climate change, landscape processes (e.g., coastal erosion), or human activity (draining, channeling of local rivers, water abstraction and impoundment, forest clearance). Wetlands can be lost to drainage for agriculture or settlement or to harvesting for commercial purposes.

Diking and drainage in the late 19th century and freshwater impoundment in the mid-20th century have interrupted the evolution of salt marshes in the upper Pamet River in Cape Cod National Seashore. These hydrologic alterations have caused vegetation to shift from salt-tolerant grasses to salt-intolerant herbs, trees, and shrubs and have caused the wetland surface to subside well below the elevation of modern, undiked marshes.

## Wind erosion

**Brief Description:** The action of wind on exposed sediments and friable rock formations causes erosion (abrasion) and entrainment of sediment and soil particles [see dust storm magnitude, duration, and frequency]. Eolian action also forms and shapes sand dunes, yardangs (streamlined bedrock hills), and other landforms. Subsurface deposits and roots are commonly exposed by wind erosion. Wind can also reduce vegetation cover in wadis and depressions, scattering the remains of vegetation in interfluves. Stone pavements may result from the deflation (removal) of fine material from the surface leaving a residue of coarse particles. Blowouts (erosional troughs and depressions) in coastal dune complexes [see dune formation and reactivation] are important indicators of changes in wind erosion. The potential for deflation is generally increased by shoreline erosion or washovers, vegetation die-back (due to soil nutrient deficiency or to animal activity), and human actions such as recreation and construction.

**Significance:** Changes in wind-shaped surface morphology and vegetation cover that accompany desertification, drought, and aridification are important gauges of environmental change in arid lands. Wind erosion also affects large areas of croplands in arid and semi-arid regions, removing topsoil, seeds, and nutrients.

**Human Influence:** Eolian erosion is a natural phenomenon, but the surfaces it acts upon may be made vulnerable by human actions, especially those, such as cultivation and over-grazing, that result in the reduction of vegetative cover.

Currently in Cape Cod National Seashore, human actions [e.g., use of ORVs (off-road vehicles) and the proliferation of social trails] influence wind erosion. Degraded areas are limited, but it is of high management significance because of the impacts on popular areas, such as Herring Cove. Aerial photographs revealed a “spider web” of social trails in this area.

## Appendix B:  Human Influences

The term "human influences" is the central theme for the second part of GPRA goal Ib4.  The term has purposefully been selected in order to explore the full breath of human activities, both inside national parks and external to the park boundaries.  Adjacent land use, consumptive activities, administrative practices, and visitor use can all influence earth surface processes.  An effective way to illustrate human influences on earth surface processes is to go through some examples.  This is not a comprehensive treatment, and these examples do not occur in all parks. These examples are provided to raise awareness, stimulate the reader's thinking, and perhaps cause the reader to contemplate additional cases from his or her own experience.

Land Use

- Agriculture – Intense use can cause loss of soil, erosion, and dust storms.  Use of pesticides can affect both surface water and groundwater quality.
- Grazing – Overgrazing can cause loss of vegetation, invasion of exotic species, soil erosion, and nutrient loss.
- Forestry – Intense logging or clear cutting creates conditions for increased erosion; eroded and transported sediment can cause increased sediment loading in streams, which could affect fluvial habitat.
- Water impoundment – This has the potential to affect one segment of a stream or river or an entire watershed.  Controlled volume of flow does not duplicate natural events, such as floods and drought.  It can affect the sediment load, change the stream morphology, and alter the habitat that is dependent on a fluvial system.
- Urbanization – This can cause a host of impacts, but a few stand outs are:  change in drainage patterns because of impervious surfaces (streets, parking lots, pavement, buildings), increased erosion, affects on surface and groundwater quality and quantity, release of toxins into the air, increased humidity in arid regions.
- Alterations to shorelines – Dredging, beach mining, river modification, installation of protective structures, and removal of back-shore vegetation can potentially alter shoreline processes, position, and morphology by changing the sediment supply, transport, and erosion.

Consumptive Use

- Groundwater withdrawal –This sustainable, renewable resource can become a non-renewable, mined one, if groundwater withdrawal exceeds recharge.  Mining groundwater is terminal and affects and entire ecosystem (both living and non-living components).  Where withdrawal has been intense for decades, the surface has been known to collapse (subside) over many acres to depths of over ten feet.
- Oil and gas production – This can cause surface subsidence and cause contamination of water aquifers and cave & karst systems.  Oil and gas operations can leave a considerable "footprint" on the land, such as roads (created during seismic tests and well operation), pipelines, facilities, storage tanks, and well pads.
- Mining (open pit and underground) – It can reconfigure the landscape over large areas bringing significant and permanent change to the landscape.  It can affect groundwater by releasing heavy metals or other chemicals into the system.
- Mineral Materials Mining – If performed in sensitive ecosystems or with respect to volume of material removed, the quarrying of stone, mining of gravel, and borrowing of soil can impact geologic process.

- Extirpation of species – This can affect both the living and non-living components of an ecosystem. Take the elimination of beaver from an ecosystem, for example. This can alter water impoundment, sediment load, timing of sediment release, and stream channel morphology.

Administrative Use

- Roads & bridges – Often these have been constructed with little or no consideration for natural processes. Roads can disrupt drainage, cause erosion, and create hillslope instability. The abutments for bridges can change the flow and morphology of streams and rivers.
- Parking lots – Construction, location, and drainage off parking lots can cause harm. Large paved areas (acres) deprive the surface of an opportunity to absorb precipitation. Water flowing from the parking lots can cause erosion and gullying if not properly directed. Runoff pollution affects surface water and groundwater.
- Facilities placed over karst and caves – Contaminants and runoff from restrooms and other water usage can reach cave and karst systems below Earth's surface and cause damage to the fragile subterranean ecosystem.
- Water consumption – Parks located in arid environments need special consideration for all aspects of water usage (restrooms, watering lawns, domestic use for staff, maintenance shops, etc.)
- Trails – If they are poorly located with respect to soil, rockwalls, wetlands, and sensitive vegetation, they have the potential to exacerbate erosion, rock falls, and slope instability. The placement of snowmobile trails can influence slope stability and cause avalanches.
- Armoring – Through engineering efforts, humans have attempted to impose stability on naturally dynamic and ever-changing environments along streams, rivers, coastlines, and shorelines. Structures interfere with the transport of sand and sediment and aggravate erosion over the long-term.
- Planting exotic species – Planting non-native species on sand dunes to hold them in place disrupts eolian processes that drive an ecosystem.
- Fire – Fires directly affect slope stability and can cause debris flows on steep slopes.

Visitor Use

- Compaction of soils – Over use by recreationists (hiking, horseback riding, mountain biking, OHV's) can compact soil, which diminishes its capability to function and maintain itself as a viable part of the ecosystem.
- Social trails – Depending on the fragile nature of the environment, wandering off-trail can seriously damage fragile resources (caves, wetlands, soil crusts, cinder cones, tundra, etc.)
- Touching fragile features – A number of geologic features have taken years to form through geologic processes, and although seemingly rock-hard, they may be fragile. Examples include stalactites and stalagmites in caves. Also included are erosional features, such as arches, bridges, hoodoos, and badlands. Crystals are another example. Visitors touching or climbing on all these features can cause irreparable damage.

Power boating – Over a period of time, wakes from small and large boats alike can contribute to shoreline erosion. Fuel contamination can affect water quality.

## Appendix C: Introducing Geoindicators

**What are Geoindicators?**

Geoindicators constitute an approach for identifying rapid changes in the natural environment. An international Working Group of the International Union of Geological Sciences (IUGS) developed geoindicators in order to access common geological processes occurring at or near Earth's surface that may undergo significant change in magnitude, frequency, trend, or rates, over periods of 100 years or less. Geoindicators measure both catastrophic events and those that are more gradual but evident within a human lifespan. Some geoindicators can provide a record of natural events through time.

The 27 geoindicators are:

1. Coral chemistry and growth patterns
2. Desert surface crusts and fissures
3. Dune formation and reactivation
4. Dust storm magnitude, duration, and frequency
5. Frozen ground activity
6. Glacier fluctuations
7. Groundwater quality
8. Groundwater chemistry in the unsaturated zone
9. Groundwater level
10. Karst activity
11. Lake levels and salinity
12. Relative sea level
13. Sediment sequence and composition
14. Seismicity
15. Shoreline position
16. Slope failure
17. Soil and sediment erosion
18. Soil quality
19. Streamflow
20. Stream channel morphology
21. Stream sediment storage and load
22. Subsurface temperature regime
23. Surface displacement
24. Surface water quality
25. Volcanic unrest
26. Wetlands extent, structure, hydrology
27. Wind erosion

**Why are Geoindicators important?**
Ecosystem management, reporting, and planning generally focus on biological issues such as biodiversity, threatened and endangered species, exotic species, and biological and chemical parameters relating to pollution (e.g., air and water quality). Much less attention is paid to the physical processes that shape the landscape—the natural, changing foundation on which humans and all other organisms live and function.

Geoindicators help answer NPS resource management questions about what is happening to the environment, why it is happening, and whether it is significant. They establish baseline conditions and trends, so that human-induced changes can be identified. Applying the geoindicators approach will provide science-based information to support resource management decisions and planning. Geoindicators help non-geoscientists focus on key geological issues, help parks anticipate what changes might occur in the future, and identify potential management concerns from a geological perspective.

Geology and geological processes are integral to park management and planning. For example, the underlying geology and soils influence natural vegetation patterns, and in turn exert a control on biological communities. Geological processes can affect park roads, infrastructure, and facilities. When measures of natural landscape change are omitted from monitoring and planning, the assumption that natural systems are stable, fixed, and in equilibrium is perpetuated. Natural systems are dynamic, and some may be chaotic; change is the rule, not the exception. Monitoring the abiotic components of ecosystems using geoindicators will help to emphasize this point.

The geoindicators approach can be a useful reminder both of the prevalence of natural fluctuations and of the difficulty of separating them from human-induced environmental change. Using geoindicators shifts management actions from response (crisis mode) to long-range planning, so issues can be recognized before they become concerns. Geoindicators may also prove to be useful tools for enhancing interdisciplinary research and communication, a way to connect with others concerned with environmental issues and problems.

**How do Geoindicators fit into the National Park Service's strategic plan?**
In 1999, the NPS Geologic Resources Division (GRD) and the NPS Strategic Planning Office cooperated to develop a Servicewide geologic resource goal as part of the Government

Performance and Results Act (GPRA). The NPS Goal Ib4 states, “Geological processes in 75 parks (36% of 270 natural resource parks) are inventoried and human influences that affect those processes are identified.” This goal was designed to increase understanding of geological processes and their functions in ecosystems and to help park managers make more informed science-based management decisions.

This goal is intended to be the first step in a process that will lead to inventory, monitoring, and research, and ultimately focus on the mitigation or elimination of human activities that severely impact geological processes, harm geologic features, or cause critical imbalance in ecosystems.

**What is the purpose of a Geoindicators scoping meeting?**
The purpose of a scoping meeting is to identify significant geological processes in a park’s ecosystem and determine if those processes are being affected by human activities. Pertinent human influences may include visitor impacts, park management practices and developments, land use adjacent to parks (e.g., pollutants, timber harvest), and global issues (e.g., industrial dust from China).

In addition, resource management issues related to geology and geological processes will be identified; and inventory, monitoring, and research studies that can provide scientific data to be used in making management decisions will be recommended.

**How does the Geoindicators scoping process work?**
The GRD coordinates efforts between park resource managers and geologists (from federal and state agencies and academia) through scoping meetings that are held in national parks. The scoping meetings are designed to use the participants’ current expertise and institutional knowledge and build on the synergy of the participants through field observations, group discussion, and the exchange of ideas. For park staff, the scoping meetings foster a better understanding of the physical resources and geological processes in the park. For scientists, the scoping meetings foster an awareness of management issues and the decision-making and planning processes preformed by park staff.

The field trip portion of a scoping meeting highlights the park’s setting and geology, as well as key resource management issues related to geological processes. During the discussion portion of a scoping meeting, selected geoindicators—specific to a park’s setting—guide and focus the dialog.

The following questions are addressed during the group discussion of a scoping meeting. The answers are rated and prioritized.

- What are the significant geological processes in the park’s ecosystems? Why are they significant?

- Which of these geological processes is being influenced by human activities both from inside and outside the park?

- How significant to park management are the identified geological processes and associated human influences?

- What sort of geological baseline data would benefit the park?

- What geoindicators should be monitored in the park? What protocols are recommended and who are the geoscientists to contact?

- Where are the information gaps? What studies or research are recommended?

- What information should be included in park planning documents?

**What are the outcomes of a Geoindicators scoping meeting?**
Scoping meetings provide an opportunity for park staff and geologists to connect and build relationships. This is significant because many park managers do not have easy access to geological expertise, and most do not have geologists on staff or in their regional offices.

Managers from participating parks will receive a summary report that highlights the recommendations identified during the scoping meeting. Recommendations include inventory and monitoring—which will provide information to use for park planning and decision-making—and research topics that will fill information gaps.

**Where can I get more information?**
- Web site about geologic resource monitoring in the U.S. National Parks: http://www2.nature.nps.gov/grd/geology/monitoring/index.htm.

- Detailed descriptions of the 27 geoindicators: http://www2.nature.nps.gov/grd/geology/monitoring/parameters.htm.

- Web site of the IUGS Geoindicators Initiative: http://www.lgt.lt:8080/geoin/welcome.

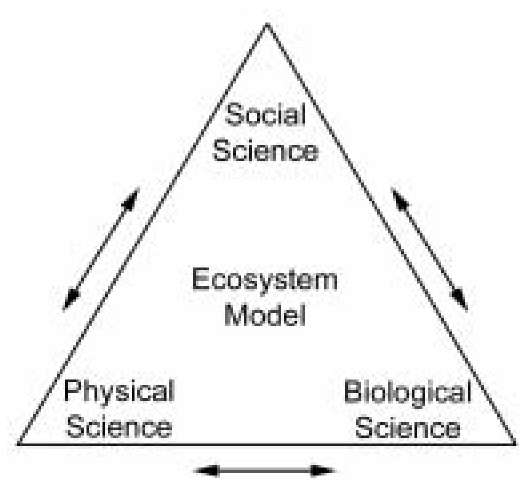
## Appendix D: Species Don't Stand Alone—Geology's Role in Ecosystems

Ecology's fundamental insight for ecosystem management is that species do not stand alone. Organisms are dynamically and interactively enmeshed in the abiotic ecosystem matrix. Increasingly, ecologists and land-management agencies are recognizing that species—the living components of ecosystems—cannot be conserved without conserving the non-living components, which help shape ecosystem structure and function (Pickett et al., 1992; Christensen et al., 1996). As "matrix sciences," physical sciences such as geology, soil science, hydrology, and climatology play a fundamental role in conservation and ecosystem management.

The founder of modern ecosystem ecology was a soil scientist, Hans Jenny (Vitousek, 1994), and James Lovelock, a geophysicist, conceptualized Planet Earth as a functional ecosystem composed of functional subsystems (Rowe, 2001). Yet despite these historical connections between the sciences and the tremendous importance of the matrix sciences to ecosystem studies, most ecosystem mangers have not traditionally integrated the biological and physical sciences in resource managment. The problem may be that most ecosystem managers/ecologists have been educated in biology departments and trained to focus on species (Rowe, 2001). Thus, the abiotic components of an ecosystem often enter management discussions as an afterthought, of secondary importance and vaguely associated with the fuzzy term "habitat," if they enter the discussion at all.

Over the last two decades, however, the focus of land management has slowly been shifting to a truly integrated, ecosystem approach—one that recognizes that species do not stand alone—and incorporates biological, geological, and social components (Figure 1). This change is particularly important as resource managers strive to gain greater predictive and mechanistic understanding of ecosystem responses to human activities. This approach identifies a need to devote increased attention to the geosciences, and especially to the interactions between the geological and biological systems.

Figure 1. Relationship of component parts to an ecosystem.




Geological processes create topographic highs and lows; impact water and soil chemistries; influence the fertility of soils, the stability of hillsides, and the flow styles of surface water and groundwater (Swanson et al., 1988). These factors, in turn, determine where and when biological processes occur, such as the timing of species reproduction, the distribution of habitats, the productivity and type of vegetation, and the response of ecosystems to human impacts. Likewise, biological processes affect geological processes. Biological activity contributes to soil formation and soil fertility, controls hillside erosion, traps blowing sand to form dunes, stabilizes drainages, and attenuates floods.

The geological resources of a park—soils, caves, glaciers, streams, springs, volcanoes, etc.—provide the physical foundations required to sustain the biological system. Human influences on geological processes and alteration of geological features inevitably affect habitat conditions. For example, the channelization of the Virgin River in Zion National Park caused the channel to incise, lowering the groundwater table and reducing the habitat of floodplain obligate species (Smith, 1998; Steen, 1999). In Jean Lafitte National Historical Park and Preserve, externally triggered land subsidence is raising the water level in the park, thereby inundating the swamp forest and reducing habitat for forest-dependent species (Sauier, 1994). Alternatively, a manipulation of the biological system can trigger changes in the geological system that can re-affect the biological system. For example, when beaver are trapped to increase the density of hydrophobic shrub species, the river morphology and sediment transport capacity change, resulting in a redistribution of the types of fish species. Geological resources also influence the impacts of natural variation in factors such as climate or human activity. The availability of water, the stability of soil surfaces, and nutrient supply from weathering rocks are all examples of underlying physical controls on biological processes.

A challenge in appreciating the relevance of geology is that geologists often work with very long time scales; whereas, life-science specialists deal with much shorter time scales. In actuality, however, geological processes occur over a variety of temporal and spatial scales. At one end of the temporal spectrum lie the processes that occur over millions of years, such as the rising of a mountain range or creation of an ocean basin. At the other end lie the processes that occur virtually instantaneously (and often catastrophically) such as floods, landslides, and earthquakes. Between these extremes is the constant, continuous evolution of a landscape over days, months, and years. Examples of these are shoreline movement, river transport of sediment, soil formation, and cave development.

Geological processes are as diverse spatially as they are temporally. The absorption of chemical elements by sediment particles may be the key process in determining groundwater chemistries. This process occurs at the microscopic level. In contrast, the geothermal activity at Yellowstone or Lassen Volcanic national parks is related to the movement of tectonic plates at a global scale.

Geological processes that most directly impact biological processes include: stream and groundwater flow, weathering and mass wasting (e.g., landslides, rockfalls), earthquakes, volcanic phenomena (e.g., eruptions, hot springs), and variation in physical and biogeochemical attributes of soils. These processes collectively operate on a variety of time scales, and it is possible for all of these processes to be operating simultaneously in a single park. For example, minor earthquakes usually accompany eruptions in Hawaii Volcano National Park, and the overall event can include landslides, stream diversion by lava flows, and buildup of topography when the lava flows solidify. These processes destroy some habitats while creating others, and introduce new substrates for early successional stages, thus maintaining habitats for early successional species (Parrish and Turner, 2001).

Even seemingly static geological resources contribute to ecosystem mosaics and biodiversity. For example, in Grand Canyon National Park, the nesting sites of spotted owls are restricted to ledges formed in a specific rock layer, the Hermit Shale. Similarly, vegetation distributions in Canyonlands National Park respond to variation in surface soil textures and elemental content. Thus, management of the nesting sites of threatened species and unique native plant habitats requires knowledge of the geological substrate. Identifying that a rock layer is important to an owl species indicates the need for integrated research. An example of floral dependence on geology is the Winkler's cactus, which grows only on the white, powdery soil and pebbles eroded from part of the Morrison Formation in Canyonlands National Park. In this case, not only is the distribution of the rock layer itself important to the plant, but the erosion products are quite fragile, requiring management of both the plant and its delicate habitat (Parrish and Turner, 2001). This same type of abiotic-biotic pattern repeats itself across the entire Colorado Plateau, a region recognized for its high frequency of plant endemism primarily because of the evolutionary constraints posed by extensive exposures of raw geologic substrates (Welsh et al., 1993).

Abiotic ecosystem components, encompassed by the matrix sciences, play central roles in shaping the distribution and dynamics of biotic systems. Nutrient constraints; water availability; disturbances in the form of landslides, floods, droughts, and eolian processes all act to constrain the composition, structure, and productivity of the terrestrial biosphere. These processes also influence the distribution of individual plant and animal species across the landscape and condition the responses of ecosystems to environmental change. In present-day ecosystems, there is tremendous variability across landscapes and through time in the ways that ecosystems respond to changes in species, climatic patterns, and land use; this variability is poorly understood. For example, how will ecosystems, and the goods and services they provide, be differentially affected by the numerous interacting components of global change: increased temperatures and $CO_2$ concentrations, altered precipitation patterns, and greater frequencies of extreme climatic episodes? This question can no longer be left to the future (McCarty, 2001; Hannah et al., 2002). From a management perspective it is crucial to identify and predict the spatial and temporal variation in both ecological vulnerabilities and services. Improved understanding of this variability would allow for more efficient, cost-effective, and sustainable use of natural resources. One of the primary hindrances to this understanding is the lack of integrative science that could facilitate ecological forecasting. In the face of rapid environmental changes, successful resource management cannot be accomplished without integrating the abiotic matrix sciences with the more-familiar biotic sciences.

These are exciting and stressful times for resource managers, as attempts to counter threats to cherished places and species are made. Disciplinary boundaries, although essential for some purely scientific tasks, are an impediment to understanding complicated issues such as preservation of ecosystems. Human attitudes and past human influences on natural systems are crucial elements in understanding what is happening and what options are available (Ludwig, 2001).

Cited References

Christensen, N.L., Bartuska, A.M., Brown, J.H., Carpenter, S., D'Antonio, C.M., Francis, R., Franklin, J.F., MacMahon, J.A., Noss, R.F., Parsons, D.J., Peterson, C.H., Turner, M.G., and Woodmansee, R. G., 1996, The report of the Ecological Society of America Committee on the scientific basis for ecosystem management: Ecological Applications, v. 6, p. 665-691.

Hannah, L., Midgley, G.F., Lovejoy, T., Bond, W.J., Bush, M., Lovett, J.C., Scott, D., and Woodward, F.I., 2002, Conservation of biodiversity in a changing climate: Conservation Biology, v. 16, p. 264-268.

Ludwig, D., 2001, Crisis and transformation: Conservation Ecology, v. 5, no. 1, article 11. [online] URL: http://www.consecol.org/vol5/iss1/art11

McCarty, J.P., 2001, Ecological consequences of recent climate change: Conservation Biology, v. 15, p. 320-331.

Parrish, J. and Turner, C., 2001, [unpublished] Life on Earth—the biogeological interface.

Pickett, S.T.A., Parker, V.T., and Fiedler, P.L., 1992, The new paradigm in ecology—implications for conservation above the species level, *in* Fiedler, P.L. and Jain, S.K., eds., Conservation biology—the theory and practice of nature conservation, preservation, and management: New York, Chapman & Hall, p. 65-88.

Rowe, J. S., 2001, In search of intelligent life: Conservation Ecology v. 5, no. 2, response 3. [online] URL: http://www.consecol.org/vol5/iss2/resp3

Sauier, R.T., 1994, Geomorphology and Quaternary geologic history of the Lower Mississippi Valley, *in* report prepared for the U.S. Army Corps of Engineers Waterways Experiment Station, I: 53-54: Vicksburg, Mississippi.

Smith, V., 1998, Development of a priority area restoration and protection plan for a moderately sized agricultural watershed in southwestern Wisconsin, *in* Rivers—the future frontier, Proceedings of the 1998 Symposium April 28 to May 3, 1998: River Management Society, Anchorage, Alaska.

Steen, M., 1999, Effects of historic river alteration on Fremont cottonwood regeneration—a case study of the Virgin River in Zion National Park, Utah: Madison, University of Wisconsin, Environmental Studies, Master's proposal.

Swanson, F.J., Kratz, T. K., Caine, N., and Woodmansee, R.G., 1988, Landform effects on ecosystem patterns and processes: Bioscience, v. 38, p. 92-98.

Vitousek, P.M., 1994, Factors controlling ecosystem structure and function, *in* Amundson, R.G., Harden, J.W., and Singer, M. J., eds., Factors of soil formation—a fiftieth anniversary retrospective, SSSA special publication no. 33: Madison, Wisconsin, Soil Science Society of America, p. 87-97.

Welsh, S.L., Atwood, N.D., Goodrich, S., and Higgins, L. C., eds., 1993, A Utah flora, Second edition: Provo, Utah, Brigham Young University, 986 p.

## Appendix E:  Park Setting

White Sands, located in south-central New Mexico at the northern end of the Chihuahuan Desert, is the largest pure gypsum dune field in the world. In 1931, the National Park Service completed a study of the area's worthiness, and in January 1933, outgoing President Herbert Hoover proclaimed 142,987 acres of white sands as a national monument.

White Sands National Monument is within an "internally drained valley" called the Tularosa Basin, which is flanked by two ranges—the Sacramento and San Andres mountains. The Monument ranges in elevation from 3,890 to 4,116 feet above sea level. There are approximately 275 total square miles of dune fields, with 115 square miles (about 40%) located within White Sands National Monument. The remainder is on military land that is not open to the public.

In the early 1940s, The United States government decided that this part of New Mexico was ideal terrain for military operations (Houk and Collier, 1994). The Alamogordo Bombing and Gunnery Range was established in 1942, just after the attack on Pearl Harbor. The first atomic bomb test detonation was made at the Trinity Site in 1945, and additional portions of the Tularosa Basin were set aside as White Sands Proving Ground. The Alamogordo Army Air Base, used for aircrew training during World War II, was renamed Holloman Air Force Base after the war. The gunnery range and proving ground were consolidated and renamed White Sands Missile Range in 1958. White Sands Missile Range surrounds the Monument and hosts a substantial portion of the dune system.

White Sands National Monument preserves a major portion of this gypsum dune field, along with the plants and animals that have successfully adapted to this constantly changing environment. Many species of plants and animals have developed specialized means of surviving in this area of cold winters, hot summers, very little surface water, and highly mineralized groundwater.

The Heart of the Sands 8-mile-long Loop Drive affords visitors the opportunity to experience the dunes. Part of the drive is paved and part is a maintained road surface on hard-packed gypsum.

Evidence of lifestyles from thousands of years ago remains in White Sands National Monument. Most notably, dozens of hearth sites have been found, some more than ten feet across. The hearth pedestals, formed not by nature but by humans, are distinctive. They contain blackened charcoal layers and are now plaster of Paris, the product that results when gypsum is heated. Repeated rains have hardened and preserved the pedestals.

References

Houk, R. and Collier, M., 1994, White Sands National Monument:  Tucson, Arizona, Southwest Parks and Monuments Association, 64 p.

www.nps.gov/whsa

## Appendix F: Park Geological Setting

The gypsum dunes of the Tularosa Basin are geologically very young features, yet to really understand the origin of White Sands we must examine a substantial amount of geologic history. This summary is intended to give a more detailed look at the major events that contributed to the formation of the world's largest gypsum dune field.

### 1. The Permian Sea

The gypsum that makes up White Sands is ultimately derived from marine rocks. Shallow seas covered much of New Mexico throughout the Paleozoic Era (570-245) million years ago). Marine deposits as old as 500 million years are present in the San Andres Mountains, but by far the most abundant sedimentary rocks in southern New Mexico are Permian in age (290-245 Ma). In the Permian Period North America was part of a great megacontinent called Pangaea, and present day New Mexico was submerged in a tropical sea just south of the equator (Figure 1). The limestone mountains at Carlsbad Caverns and Guadalupe Mountains National Parks represent the remains of a large barrier reef that was part of this Permian sea. In the middle of the Permian Period there was a major fall in sea level, causing vast stretches of water across southern New Mexico to nearly dry up. It was during this drying-up phase that large quantities of gypsum rock were deposited.

Gypsum is an evaporite mineral, meaning that it forms almost exclusively when dissolved ions become concentrated due to the evaporation of water. If sea water of normal salinity is reduced to about 20% of its original volume through evaporation, calcium ($Ca^{2+}$) and sulfate ($SO_4^{2-}$) ions will be concentrated enough for gypsum ($CaSO_4{\cdot}2H_2O$) to begin to crystallize. The cycles of evaporation that took place in the middle Permian caused hundreds of feet of gypsum to settle out onto the sea floor. Much of this gypsum is found in the 1500 ft. thick Yeso Formation, which outcrops in the San Andres and Sacramento Mountains surrounding the Tularosa Basin. "Yeso," by the way, is Spanish for gypsum. Good roadcuts of the Yeso Formation are rare, but there are a few places in the Sacramento Mountains (e.g. mile 14 on Highway 82, just before Cloudcroft) where patches of white gypsum are visible, most of which has been leached out of the original rock.

### 2. The Laramide Uplift

Near the end of the Cretaceous Period (~70 million years ago), the Rocky Mountains began to form. White Sands National Monument is about 200 miles south of the Rockies, but the same compressional forces that formed the Rocky Mountains also uplifted the marine rocks in southern New Mexico. The cause of the Rocky Mountain uplift (known as the "Laramide orogeny") is not entirely known, but most geologists believe a change in the geometry of tectonic plates was responsible for the mountain building.

The surface of the Earth is divided into seven major “plates.” These rigid plates are constantly shifting, diverging from each other in rift zones (e.g. in the middle of the Atlantic Ocean) and colliding together along convergent plate margins (e.g. off the west coast of South America). When relatively thin (40-50 miles thick), dense oceanic plates collide with thicker, less dense continental plates, the oceanic plate will sink beneath the continental plate in a process called “subduction” (Figure 2A). Subduction causes a great deal of compression across the plate boundaries, resulting in the uplift of a mountain chain adjacent to the boundary. The Andes mountain range is South America is an excellent example of a subduction-formed mountain belt. In the Jurassic and Cretaceous Periods subduction beneath the North American plate resulted in uplift and volcanism along western North America. Towards the end of the Cretaceous the angle of subduction beneath the United States became increasingly shallow, transferring compressive forces to the east. This eastward shift of compression is believed to be responsible for the formation the Rocky Mountains (Figure 2B).

The Laramide uplift affected a very broad region, including the White Sands area. If it were not for this geologic event the elevation of southern New Mexico would be substantially lower.

**3. Formation of the Tularosa Basin**

The Tularosa Basin is essential to the existence of White Sands. With no drainage outlet, this basin traps and concentrates all the dissolved gypsum that comes down from the marine rocks in the surrounding mountains, gypsum that would normally be carried away by rivers or streams.

The formation of the Tularosa Basin is part of a large-scale tectonic event that began approximately 30 million years ago and continues today. Sometime prior to the onset of this tectonic event, the shallow subduction off the California coast ceased and a new, parallel-motion plate boundary formed (now represented by the San Andreas Fault). For reasons that remain unclear, this shift in tectonic regime caused enormous upwellings of magma from the Earth's mantle. These mantle upwellings stretched apart large portions of crust in the southwest, forming the Basin and Range - a geologic province that extends from southern Oregon down to northern Mexico (Figure 3). A linear arm of the Basin and Range, known as the Rio Grande Rift, extends from southern New Mexico into central Colorado.

As the crust pulled apart in the Basin and Range, numerous fault zones developed. Large blocks of crust subsided thousands of feet along these faults, forming basins in between fault-bounded mountain ranges. The Tularosa Basin, at the southern end of the Rio Grande Rift, is just one of the many basins in the U.S. southwest that have formed due to crustal extension (Figure 4). Geologists believe that much of the basin formation associated with the Rio Grande Rift occurred within the last 10 million years.

**4. The last Pleistocene Ice Age**

The wet climate during last ice age (approximately 24,000 to 12,000 years ago) played a major role in the formation of White Sands. In the late Pleistocene Epoch, the Tularosa Basin (and much of the U.S. southwest) received substantially more rain than it does today. Cooler and wetter conditions enabled a small glacier to form on the north slope of 12,000 ft. Sierra Blanca, and much of the Tularosa Basin was filled with an enormous lake called Otero (Figure 5). Heavy rainfall flushed large quantities of soluble gypsum from the San Andres and Sacramento Mountains down to the Lake Otero. The lake became saturated with dissolved gypsum.

As the ice age came to an end, the climate of the Tularosa Basin became increasingly more arid. Lake Otero slowly dried up, leaving behind enormous deposits of gypsum. The relatively slow rate of evaporation, combined with saturated, muddy conditions along the edges of the lake, allowed the dissolved gypsum to crystallize as selenite "discs" and bladed crystals (Figure 6).

These crystals are still forming today, but the majority of selenite at Lake Lucero crystallized as the ice age lake dried up. Following the evaporation of this enormous lake, large stretches of the Tularosa Basin must have been as littered with selenite crystals as Lake Lucero is today.

The wet ice age climate was critical in flushing large quantities of gypsum from the mountains down into the Tularosa Basin. In addition, an extensive clay layer deposited by Lake Otero is largely responsible for the dune field's shallow, perched water table. This shallow water table is not only essential to plant life in the dunes, but it also enables selenite formation to continue today.

**5. Dune formation** (reviewed and edited by Steve Fryberger, March 8, 2003)
It is not precisely known when gypsum dune formation began in the Tularosa Basin. Dating techniques by Stephen Stokes of Oxford University of a partly lithified, “fossil” dune terrain just northeast of the NE30 observation station indicates that some dunes may have formed as long ago as 16,000 years BP (before the present). This date seems a bit perplexing when considering that much of the Basin was probably covered by Lake Otero at the time. It is possible that the date is inaccurate, because there was so little quartz material in the original sample that could be used for dating (Stokes, 2001, personal communication). On the other hand, the NE 30 site roughly at the same level as the Lake Otero Highstand at approximately 3950-4000 feet above sea level. It is possible that there was a local evaporative period approximately 16,000 years ago which would have caused lake level decline, allowing a small dune field to form. Of course, most of the gypsum would have been released not during the lake high stand, but upon extreme contraction of the lake and the concentration of evaporites. Thus, the most reasonable thought is that the "fossil dunes" were undoubtedly formed at sometime after the Lake Otero Highstand—although topographic relationships allow this formation to potentially have occurred early in the process of lake retreat.

In any event, it appears clear from the limited thermoluminescence dates at hand, as well as regional geology, that a major dune-building episode in the region probably began somewhere around 6500-7000 years ago. Such a chronology would fit patterns recorded nearby at Lake Estancia and by other workers in the basin (Note: see Brenda Buck’s thesis and discussion of her chronology in my report).The present White Sands dune field most likely did not begin to form until a substantial portion of Lake Otero had dried up. Some [fossil?] dunes northeast of Lake Lucero have been dated at 6,500 years (S. Stokes, personal communication). This date is most likely representative the large-scale dune formation event that defined the present White Sands. The present day dunes, which overlay 25-30 feet of gypsum sand in places, are quite young from “yesterday” to perhaps hundreds of years in age. Subsurface crossbedded dune deposits such as those cored by Eddie McKee in his landmark studies are probably more representative of the 6500 year time period. Clearly, further work on dating of the dunes would be very helpful. However, it can be safely asserted that White Sands is geologically very young, and that the dune field has probably formed during multiple episodes of deflation of Lake Otero gypsum deposits.

All of the gypsum sand in the dune field was formed by the breakdown of selenite crystals, most of which represent recycling of gypsum crystals from the evaporite phase of drying Lake Otero (Figure 7). These crystals occur in a variety of shapes and sizes, commonly twinned. All selenite is typified by the presence of mica-like cleavage planes. Expansion and contraction caused by large temperature fluctuations and periodic freezing serve to break up selenite crystals along these planes. When crystals become small enough to be transported by wind, further breakdown, and rounding will occur. Gypsum is one of the softest minerals. Gypsum sand will be broken down into smaller grains much more rapidly than quartz sand when transported by the wind. This effect can be plainly seen when comparing coarse crystal grains near Lake Lucero to very fine sand near the eastern edge of the dune field. Although very little new gypsum is forming today, wind erosion of the gypsum-bearing sediments of ancient Lake Otero continues, along with the breakdown of the small gypsum crystals to produce sand. This process, rather than contribution from Playa Lucero, is the main process feeding the most active portions of the dune field. Indeed, the dampness, mud and evaporite cementation of Playa Lucero has reduced gypsum throughput so greatly that areas downwind of Playa Lucero are subregional scour areas where partly lithified gypsum dunes are being eroded due to insufficient sand contribution from areas upwind.

Gypsum sand formation continues today. At the same time, however, sand is being broken down into silt size particles that are blown out of the Tularosa Basin. Whether or not the net size of the dune field is growing or shrinking remains to be seen, however the dune field leading edge is advancing to the northeast.

## Appendix G: Compilation of Notes taken during Scoping Session

## January 29, 2003

Dune formation and reactivation

**Issues**
- Links to global climate change
- Vegetated and parabolic dunes are particularly susceptible to effects of climate change
- Some of the classic work on dunes in the world was preformed at White Sands—References:

  McKee, E.D., 1966, Structures of dunes at White Sands National Monument, New Mexico (and a comparison with structures of dunes from other selected areas): Sedimentology, v. 7, no. 1, Special Issue, 136 p.

  McKee, E.D., 1971, Growth and movement of dunes at White Sands National Monument, New Mexico: U.S. Geological Survey Professional Paper 750-D, pp. 108-114.

**Importance to ecosystem**
- White sands affect species; 6-14 white species/"local populations"
- World's largest gypsum sand dunes
- 275 square miles (144,000 acres) of dunes in Monument; over 50% of Monument
- 400 square miles—total size of dune fields
- Significant relationship with groundwater
- Groundwater quality is poor for consumption but important to geologic system; high salinity affects production of gypsum, which is the primary constituent of the dunes; change in the salinity balance would cause change in dune system; in short, less salinity = less gypsum = less material for dunes

**Human influences**
- Road "plowing" (limited extent to "Heart of the Sands" Loop Road)

**Management significance**
- Dunes are the primary resource
- Monument established in 1933 because of the dunes
- Protection of the dunes is stated in the enabling legislation
- Concern for public access—enjoyment vs. protection
- Managers have a responsibility to interpret dunes to the public; need accurate information in order to interpret properly

**Inventory**
- Aerial photography—repeat over time to document sand movement
- Good, existing aerial photographs that have been geo-referenced
- Orthotopo maps (photography superimposed on topography) available from UTEP

- Need map of individual aeolian features (e.g., variability of parabolic dunes, salt flat region, basins, active dunes, sand sheets, etc.)
- Need compilation and organization of references—funding available from Geological Society of America, and NPS Geologic Resources Inventory (GRI) and Geoscientist-in-the-Parks (GIP) programs
- Topographic transects are being done by UTEP

**Monitoring**
- Repeat GPS measurements on dune movement

**Research**
- Need an overall understanding of dune processes, including interaction of groundwater (e.g., perched water tables), wind velocity, and vegetation
- Need to understand dune processes: movement, stratigraphy (studied for the most part)
- Need to better understand unsaturated zone, information is only anecdotal at this point
- Research proposal could be prepared by Rip Langford and Bobby Myers
- Understand fossil dunes (Contact: Curtis Monger and Andrew Valdez)

### Dust storm magnitude, frequency, and duration

**Issues**
- Playas contribute to airborne dust
- WHSA has a Class 2 air quality designation because it is not a park or a wilderness area, rather it is a monument
- Regional influence of being part of the Southwest, including population growth/urbanization in arid region

**Importance to ecosystem**
- Dust storms affect soil crusts
- Part of an aeolian system
- Habitats have evolved to cope with (survive because of?) dust storms
- Significant for gypsum formation
- Playas are a source of dust

**Human influences**
- Legacy issue of overgrazing
- Population growth of the region; construction in urban areas causes increased dust storms—not necessary a problem for WHSA at this point in time

**Management significance**
- Particular size of particles are health hazards
- Air quality and visibility concerns

**Inventory**

- Questions: What are the size and composition of particles? What's being eroded? What amount is being eroded? Wind velocities? How long do particles stay in suspension? How high do particles go? What is the duration of dust storms?
- Some data are available from the 1960s when monitoring was done with a camera on the missile range
- Typically dust storms last on the scale of hours

**Monitoring**
- "Improve stations" collect dust, carbon, etc.

## Wind erosion

**Issues**
- Primary story for park interpretation
- Gypsum is corrosive on steel

**Importance to ecosystem**
- Landscape shaped by wind erosion
- Lake Lucero—60 foot deep depression formed by wind erosion; lake partially refilled
- Active, ongoing process
- Dune fronts move more slowly because of the stabilizing effect of vegetation than back of dunes

**Human influences**
- Legacy impacts of overgrazing
- Roads

**Management significance**
- Impacts cultural resources (especially hearth sites); wind erosion picks away at sites
- Staff time is used in keeping road open and accessible to visitors
- Managers need to consider wind erosion in the future development of facilities, park planning, interpretation, and maintenance current facilities, e.g., road, trails, fences, restrooms

**Inventory**
- Variety ('patchwork") of landscapes/habitats created by wind erosion—hasn't really been studied in the park

**Research**
- Information on west slope and playa is necessary for accurate interpretation and public information
- Alkali Flats area would be a good location to study wind erosion, but it is remote

## Groundwater chemistry in the unsaturated zone

NOTE: In the context of WHSA, the physical and microbiotic components of the unsaturated zone are also significant, not just groundwater chemistry.

**Issues**
- Significant relationship to dunes
- According to Fryberger, main process that controls dunes is moisture, which produces a "crust surface" that preserves dunes
- Dunes have water table defined surface, capillary attraction/fringe; may not necessarily be a function of cementation
- Capillary fringe at subsurface is tied to stability of dunes
- Subsurface wicking controls stability of areas, creates hard layers, ground surface rises and falls with rise and fall of water table

**Importance to ecosystem**
- Important for formation of soils
- Unsaturated zone is important because it is the available water holding capacity for plants (both amount and quantity of water); sands have water that may not be saline and may be available for plants
- Rainwater is source of water in unsaturated zone (aka "vadose zone")
- Determines kinds of vegetation

**Management significance**
- Significant (5) because of the affect on dunes, vegetation, and other resources

**Inventory**
- USGS funding to look at contaminants in park from Lost River in unsaturated zone
- Available information from the Jornada Long-Term Ecological Research project (Contact: Curt Monger), on-going study <http://jornada-www.nmsu.edu>
- Rick Huff has well data and park funding

**Monitoring**
- Install monitoring wells in a variety of environments (with piezometers)
- Need long-term monitoring; maybe more frequently than quarterly

**Research**
- Need to identify questions and purpose of study on unsaturated zone
- Contacts at meeting for developing/defining study: Pete Penoyer, Bruce Allen, Bill Reid, Rip Langford, Rick Huff, Anne Marie Matherne
- Need to understand aquatards (Contact: Andrew Valdez)
- ADDITION: Need to identify the interaction/intercommunication (if any) between perched water table of the dune fields and the regional water table of the basin. Are there intervening aquitards (leaky), aquicludes (salt/halite beds), unsaturated porous and permeable intervals, clay hardpans etc.? What is the vertical separation of shallow and deeper saturated zones? DO perched and regional water tables merge in wet years to become one? (Pete Penoyer, written communication, February 24, 2003)

Groundwater quality

**Issues**

- Public water supply is from Alamogordo, not groundwater within park
- Not exploitable as a resource for human consumption, too saline
- 10,000 mg/L is afforded protection by EPA, e.g., MW #5
- ADDITION: The long term affects of groundwater withdrawal and encroaching growth and development on local recharge to the perched aquifer at the monument (Pete Penoyer, written communication, February 24, 2003)

**Importance to ecosystem**

- <3,000 mg/L—wildlife consumes this water

**Human influences**

- Rocket fuel (solid and liquid), missile crashes
- Perchlorate (contained in solid rocket fuel) doesn't degrade in groundwater
- Hydrazine (liquid rocket fuel); UV light degrades it, degrades over time
- Missile crash (December 1999) may be a source of hydrazine; no detection in fall 2002
- Local contaminants may be an issue (e.g., evaporation ponds)

Additional notes (Rick Huff, written communication, February 4, 2003):

I would say that human impact on groundwater quality is low to non-existent (give it a 1) based on all the analyses we did for ground water on the Monument. Impact of surface water (Lost River and possibly Lake Lucero) is pretty much unknown.

**Management significance**

- Unknown

**Inventory**

- USGS made thorough inventory in 1999 and found no contaminants
- Level 1 Water Quality report available from NPS Water Resources Division; report looked for potential impact from Holloman AFB
- Holloman report performed by consultant
- Sampling design should include water quality, combined with water level
- Incorporate groundwater quality into overall model to include level and quality; basin-wide model by USGS

**Monitoring**

- Monitoring wells could test chemistry/quality; design sampling program

**Research**

- Interesting to study: geochemistry and its effect on dune stabilization, redox potential

## Groundwater level

**Importance to ecosystem**

- Major controlling factor for dunes
- Provide stability for dune fields, i.e., if water table is lowered, dunes will become more active
- Vegetation and physical crusts are also factors in stability

**Human influences**

- Some pumping of the Lost River (a recharge for groundwater). CORRECTION: There is no pumping from Lost River; rather, water that would historically have flowed into Lost River is now intercepted by spring boxes in the Sacramento Mountains (Rick Huff, written communication, February 12, 2003).
- ADDITION: Much of the flow that would be Lost River was originally diverted by the settlers of La Luz starting in the 1860s. Subsequently, Alamogordo "completed" the diversion by obtaining upstream water rights. The only appreciable flow that makes it to the footslope/basin/infiltration portion of Lost River results from summer thunder storms and post snow runoff (Andrew "JR" Gomolak, written communication, March 5, 2003).
- ADDITION: I would argue that there is a legitimate long term concern about possible ground water drop due to pumping for desalinization, which is under development about 10 miles northeast of Alamogordo. This is going to happen, thanks to Congress paying for it; however, no one knows the probable long term ground water effects—other than that it is reasonable to expect an overall drop in groundwater elevation. This could significantly affect WHSA (Andrew "JR" Gomolak, written communication, March 5, 2003).
- In general, human influence is unknown; USGS model may assist with this assessment

**Management significance**

- High—affects dune movement, vegetation, and other resources

**Inventory**

- In 1999, the missile range did a range-wide water level measurement (Contact: Bob Myers)
- No long, continuous data within the park
- Need baseline data to plan for future development outside the park
- Determine past impacts; compare pre-development to 1995 levels

**Monitoring**

- Need monthly monitoring of groundwater level
- May be a seasonal signal, so monitoring must capture that
- Groundwater level has annual-seasonal cycles
- A network of monitoring wells could be established (Contact: Bruce Allen, Rick Huff); Great Sand Dunes NP has a model that could be used (Contact: Andrew Valdez)
- Model needs to include: extent of aquatards and flow direction

ADDDITIONAL NOTES (Pete Penoyer, written communication, February 24, 2003)

- Need to accurately survey in monitoring well elevations so that true groundwater flow direction might be established.
- Detailed stratigraphic description of units, hydraulic properties and water bearing condition

- Telescope regional model to park scale and understand relationship to perched aquifer
- Need to identify possible cooperating agencies that would undertake a variety of investigations in a team effort and the resources they might offer

**Research**
- Need a conceptual model of regional/basin-wide groundwater dynamics
- Basin and range has multiple groundwater systems (shallow, medium, and deep); focus has been given to shallow
- Need to understand saline groundwater systems
- WHSA needs to be interpreted using a basin-wide model, basin-level approach
- USGS is developing a basin-wide model (Tularosa Basin); first draft is under review at present time; could take 1-2 years for completion (Contact: Rick Huff)
- "Telescope" regional model to park scale
- Aspects of study: flow direction, water levels, effects of water pumping, disposal of desalinization products

### Lake levels and salinity

**Issues**
- Focus on Lake Lucero and arroyos
- Lake Lucero is 2nd most important asset after dunes
- 1933 "founders" saw significance for preserving Lake Lucero as part of Monument
- Preserves a source of sand; Paleozoic rocks in San Andres Mountains west of the Monument are ultimate source

**Importance to ecosystem**
- Links to regional groundwater system
- Part of dune system

**Human influences**
- Monthly public (supervised) walks with park interpreters to Lake Lucero

**Management significance**
- Research findings will have a major influence on Interpretation, including written materials, presentations, telling visitors about source of sand for dunes
- Research may cause major shift in thinking about dune formation; this has major impact on Interpretation
- Lake Lucero tells story of gypsum sand formation, and ultimately dune formation

**Inventory**
- Determine amount of groundwater vs. surface water in Lake Lucero
- Determine what salts are produced and when

**Monitoring**
- Inexpensive to set up monitoring of lake levels (Contact: Rip Langford)

- Possibly use automated system because of access
- Install shaft encoders/dataloggers called “aqua pods” to measure water level or use manual measurement; Great Sand Dunes may have an extra aqua pod to loan WHSA (Contact: Andrew Valdez)
- Accessible sites use manual measurements; less accessible sites use dataloggers (Contact: Anne-Marie Matherne)
- Recommendation: Form a workgroup to determine sampling program, including lake levels and changes in water chemistry as a function of lake level

**Research**
- Important to understand resource, including source(s) of sand, streams carrying sediment to lake
- Understanding the Lake Lucero system feeds into other things, e.g., dust storms, what salts are produced at what times

## Streamflow

**Issues**
- Dunes moved and covered Lost River
- Recharge for groundwater
- Lost River is the only stream that enters the park; ephemeral and not areally significant
- Arroyos on west side of park run only during storm events
- Very localized summer storms (July-August), thunder storms

**Importance to ecosystem**
- Lost River (outside the park) is habitat for pup fish (live in saline waters)—state listed endangered species
- Annual rainfall cycles are important
- Rainfall influences cyanobacteria “blooms”
- Surface water important for burrowing animals
- Surface water and precipitation input are important for Lake Lucero
- Playa system is dependent on surface water influx
- Affects mobilization of gypsum sand/dune formation

**Human influences**
- Lost River is dewatered by Alamogordo and ranching
- Population growth caused increased water use and lowered levels of Lost River
- Culverts on range roads (#7 and #10) influence flow regime; roads inhibit surface flow across alkali flats (Range Road 10); roads serve as berms; culverts concentrate flow and increase erosion
- Archeological sites are affected by concentrated flow produced by culverts (vs. sheet flow); eroded soil from archeological sites
- Roads were under-engineered for storm events

**Management significance**

- Concerns for damage to archeological sites caused by erosion
- Principal damage to sites has been done; damage is now incremental
- Potential partnering between park and WSMR to mitigate further damage to archeological sites
- ADDITION: Arroyo downcutting, impact on plant communities and other natural processes (Bill Conrod, written communication, February 25, 2003)

**Inventory**
- Measure affected bajada that flows into playa
- Use topographic maps for inventory of arroyos
- Photo documentation above and below the roads to document human influences
- Temperature and precipitation record from 1916 to present in Alamogordo
- Temperature and precipitation monitoring occurs in the park, since 1960s

**Monitoring**
- Monitoring extreme events, e.g., 1 foot per hour of rainfall during summer storms; monitoring needs to consider storm events
- Use crest stage gage to measure peak flows during storm events; useful because of site inaccessibility. ADDITION: In addition to crest stage gages, temperature sensors buried beneath the stream/arroyo channels can provide cheap data on the frequency of flow (Rick Huff, written communication, February 12, 2003)

### Surface water quality

**Issues**
- Focus on Lost River

**Importance to ecosystem**
- Unknown

**Human influences**
- Limited sources of contaminants: Holloman AFB (Lost River flows from east through Holloman; rocket fuel facility near Lost River) and missile crashes
- Concerns for contaminants (hydazine) entering Lost River from nearby rocket test tracks facility CORRECTION: Concerns for contaminants (perchlorate) entering Lost River from nearby solid fuel rocket facility (Bill Conrod, written communication, February 25, 2003)
- Concerns for hydrazine rocket fuel from missile crashes
- One Air Force facility and one NASA facility ("tenant" of WSMR) upgradient from park
- ADDITION: the possibility of contamination is likely low and human health risk very low due to site remoteness and lack of an exposure pathway (Pete Penoyer, written communication, February 24, 2003)
- 

Additional notes (JR Gomolak, written communication, February 4, 2003):

The perchlorate is fallout from solid rocket engines used over the years. Some are still in service at the test track. Monitoring of potential runoff into the Lost River "playa" is an integral part of the Holloman Storm Water Pollution Prevention Plan, but we haven't had any runoff to monitor.

Hydrazine is an oxygen bearing additive for liquid fueled rockets, some aircraft, and nitromethane burning fuel dragsters. There have been no liquid fueled rockets at Holloman since the early 1960s. The aircraft that used hydrazine as a fuel supplement have been gone for about 15 years, and no new aircraft using hydrazine are in the Holloman air craft inventory. Hydrazine is highly volatile, and any concentrations (none are known) would have dissipated rapidly, thus the likelihood of any detectable quantity remaining is vanishingly small. [Above is true for Holloman AFB, but the Army at White Sands Missile Range still uses old hydrazine fueled missiles as targets for testing anti-missile systems (Bill Conrod, written communication, February 25, 2003).]

There is a possibility of perchlorate transport into Lost River; however, the concentrations will be exceedingly small. There is currently no minimum allowable standard, although there is some possibility that a "clean-up requirement" maximum may be established near 10 parts per billion (that's a VERY small amount!), which will likely only apply to drinking water and potable water sources, which the Basin water is not. [No EPA rule on pechlorate but California has a 10 ppb limit in drinking water (Bill Conrod, written communication, February 25, 2003).]

The Air Force has conducted a major study at multiple locations across the United States, to assist the EPA in defining the presence of perchlorate. At Holloman, 182 samples were taken from wildlife, vegetation, soil, and groundwater. Of those, 30 samples had detectable levels, for which the mean detection was 10.9ppb. Some of the amounts detected in terrestrial vegetation, at the building near the south end of the Test Track, are well above that level (238ppb, 310ppb). The Air Force is awaiting the decision of the EPA on the cleanup level.

So, it would be reasonable to have monitoring wells, occasional surface water sampling, and occasional vegetation sampling, along the water course in that corner of WHSA, so that when a level is established, the extent of the risk and cleanup required can be better determined; any potential threat to WHSA can be quantified and included in the cleanup if appropriate.

Additional notes (Rick Huff, written communication, February 4, 2003):

I would say that human impact on groundwater quality is low to non-existent (give it a 1) based on all the analyses we did for ground water on the Monument. Impact of surface water (Lost River and possibly Lake Lucero) is pretty much unknown. [Data gathering will be done during summer of 2003 to better establish status of contaminants in park soil and ground water (Bill Conrod, written communication, February 25, 2003).]

**Management significance**

- Contaminants are a "political issue" because of Holloman AFB and White Sands Missile Range
- Park mangers would need to respond to contamination of surface water; risk is low, however

**Monitoring**

- Sample salt cedars on edge of dunes
- Surface water sampling is tricky (intermittent flow); therefore, use salt cedars
- USGS is going to use salt cedars leaves as indicator of contaminants
- Question: Do the salt cedar leaves have perchlorate (thyroid depressor for vertebrates)?

### Wetlands extent, structure, and hydrology

**Issues**

- Concern is that wetlands have been lost
- Used to have wetlands with cattails, past evidence of high water
- In a dry environment, "wet areas" are important because of the scarcity of water
- Much anecdotal evidence, e.g., distant frogs heard from housing area over ten years but not now, implying decline of amphibians due to unknown causes
- 

**Importance to ecosystem**

- Wetlands have components of hydrology, soils, and vegetation
- Habitat and loss of habitat if water table goes down
- Water retention is important
- Past evidence of high water areas
- Biodiversity, affect species diversity
- Naturally driven system
- Water table issue—affects sand transport/dune stability
- Indicator of long-term precipitation trends

**Human influences**

- Holloman AFB (just outside park boundary) had sewage treatment system that augmented wetlands; new facility meets standards but temporary discharge area created wetlands between time of closure and new plant
- ADDITION: The old Holloman wastewater plant created sewage lagoons, which fed adjacent wetlands. It was located adjacent to a natural playa/ponding area, so the wetlands were not created by the treatment plant, but were increased in area by interaction with the water infiltration from the old lagoons. However, those lagoons had to be closed due to contamination from "pre-environmental-concern" activities. The new sewage plant was designed to feed effluent to new wetlands constructed specifically as a condition of an agreement that governed the closure of the old lagoons (Andrew "JR" Gomolak, written communication, March 5, 2003).
- Garton Pond (artesian well, human drilled); warm, saline water flooded surface; saline waters now being brought up and contaminating brackish waters. CORRECTION: This isn't quite correct as the pond watered by the artesian flow has sunfish stocked in it for fishing. I don't know of any hard data on old well flows or current seep (Bill Conrod, written communication, March 13, 2003).

**Management significance**

- Naturally driven system, therefore not much that management can do about it

- Concern for loss of species

**Inventory**
- Need inventory of wetlands (Contact: Joel Wagner, NPS Geologic Resource Division)
- Continue/extend study performed on missile range; 9 year study that just finished the data collection phase
- Use same classification as missile range; different approach than using standard criteria (i.e., hydrology, soils, and vegetation)
- Information may be gathered from analysis of aerial photographs (some from early 1940s); aerial surveys also occurred in 1984 and 1996; see changes over time in photos; ground truthing needed in addition to photo interpretation
- Look at areal extent and change over time
- Keep eye on city of Alamogordo (i.e., development outside park)

**Monitoring**
- Monitor extreme, storm events
- Question: Do interdune areas flood during storm events?

**Research**
- Question: Why did water levels go down?

### Soil quality

NOTE: Soil quality defined as the ability of soil to function: supply water, nutrients, stability to plants

**Issues**
- Resources: NRCS and Soil Quality Institute in Las Cruces
- Losing soil quality (water holding capacity) on western slope because of erosion, loss of fine material, 10% of park land
- Desertification—decline of quality of soil and vegetation, ADDITION: Loss of grass and other fine plant material holding soil with resulting accelerated erosion (Bill Conrod, written communication, February 25, 2003)
- World class study area at Jornada Experimental Range Station that could serve as model for park

**Importance to ecosystem**
- Gypsum soil—low diversity, high specialization of plants

**Human influences**
- Overgrazing
- Historic ranching
- Roads

**Inventory**

- NRCS map (1970s) needs to be remapped at more useful scale (Contact: Pete Biggam, NPS Soil Scientist)
- Reference: Neher, R.E. and Bailey, O.F., 1976, Soil survey of White Sands Missile Range, New Mexico, parts of Otero, Lincoln, Doña Ana, and Soccorro counties: U.S. Department of Agriculture, 64 p.

**Monitoring**
- Erosion monitoring devices: erosion pins, sediment traps

## Soil and sediment erosion

NOTE: Functions associated with the geoindicators "Stream channel morphology" and "Stream sediment storage and load" were discussed in the "Soil and sediment erosion" geoindicator. Particular attention was paid to bajadas.

**Importance to ecosystem**
- Bajadas (piedmont landforms) are a distinct ecosystem; basin and range landform, morphological feature
- Bajadas distribute water; coalesced system of alluvial fans
- Bajadas have distinct plant communities, distinct soil types
- Bajadas are recharge area for water (once past caliche area)
- Lake has truncated the base of bajada, steepened toe of slope (debris flows)
- Erosional scarp along lake formed by water (waves) then later eroded by wind

**Human influences**
- Culverts on roads causes accelerated downcutting
- Overgrazing—legacy issue (pre-WWII)
- Change in plant communities: loss of fine plant material; changing from grasslands to shrubs; grasslands to mesquite-and-creosote to mesquite dominated
- Erosion affects vegetation and animals
- Concerns for archeological sites, e.g., NW corner of park at Huntington Site
- Fiber optics cables cut straight line that becomes a "speedway" for water

**Management significance**
- Soil and sediment erosion is a huge driver, if park managers want to prevent damage and degradation of archeological sites as mandated by federal law and NPS policy

## Desert surface crusts and fissures

**Issues**
- Soil crusts greatly affect precipitation that falls on them
- Increased (accelerated) erosion without crusts
- Crusts in WHSA are robust and recover readily (in comparison to areas on the Colorado Plateau)

**Importance to ecosystem**

- Crusts bring nitrogen into the system for the use of plants
- Crusts promote and curtail erosion (site specific); sandy—increase runoff, silty—increase infiltration
- Filaments of cyanobacteria are hydrophobic
- Crusts promote the lateral redistribution of water (vs. infiltration of water which is typical in dunes)
- Crusts possess a soil binding capability
- Crusts are an indicator of ecosystem health
- Indicators of climate change (e.g., rainfall and solar radiation)
- Crusts are critical to plant growth
- Crusts are susceptible to burial (a few millimeters can kill)
- Crusts hold an intermediate position (habitat): not in active dunes or stable dunes; between barren and vegetation
- Fissures are not an issue for WHSA; there are some in the playas on the missile range

**Human influences**

- Use of ATVs for management purposes (e.g., oryx removal project, search and rescue, accessing archeological sites) affects crusts
- Public use area is areally limited to end of road; also not much crust there, mostly physical (vs. biotic) there

**Management significance**

- Park managers don't know enough about soil crusts to give a high rating; potential problems are unknown
- Important to perform baseline data gathering, especially for use in the future

**Inventory**

- Missile Range has some data (veg plots) that overlap onto park
- Holloman AFB has performed a 5-year study on resilience of crusts (Contact: Hildy Reiser)
- UTEP has spectral analysis of WHSA; could identify crusts from recently-gathered data, needs ground-truthing, however (Contact: Phil Goodell)
- Could develop IR signature for crusts
- Need (to create) a map of the spatial distribution of crusts (habitat dependent); start with soil map; use AVRIS imagery from UTEP (Contact: Phil Goodell); highlight rain events
- Need to determine rates of recovery
- Different types of crusts exist (mosses, lichens, cyanobacteria, and physical); rates of recovery varies with each type
- May be able to partner with White Sands Missile Range—funding potential
- WSMR has several hundred plots since 1980s; interested in recovery from horses
- 1st step—Compile existing information: (1) data from WSMR, (2) Holloman AFB data (Contact: Hildy Reiser), (3) park photo plots (ATV study in 2000 and 2002), (4) UTEP AVRIS imagery (Phil Goodell)
- May be able to use a Geoscientist-in-the-Parks (GIP) for compilation project (Contact: Judy Geniac, Geologic Resources Division)

**Monitoring**

- Photo-plot monitoring of crusts (2000) on a variety of soil sites; rephotographed (Spring, 2002); no other monitoring
- Once inventory is established, monitoring is important because of dune succession and movement
- Multi-scale monitoring; once every 3 years
- Rain dependent coming to life; have a team ready to monitor after a rain—SWAT approach
- Regular sampling intervals may not provide a lot of information; need to target rain events

### Seismicity

**Issues**

- Low probability of seismic event in next 50 years
- Fault zone east and west of Monument
- Monument may be affected by ground shaking and liquifaction

**Importance to ecosystem**

- WHSA is located in a tectonic setting, i.e., Rio Grand Rift
- Tectonic setting dictates location of dune field

**Management significance**

- Rio Grand Rift is important to "story" of park
- Topic for public education—there are quakes in New Mexico and the public can protect themselves and their property with minimal effort (e.g., tie down water heaters)
- Reference
  Machette, M.N., 1987, Preliminary assessment of paleoseismicity at White Sands Missile Range, southern New Mexico—evidence for recent timing of faulting, fault segmentation, and repeat intervals for major earthquakes in the region: U.S. Geological Survey Open-File Report 87-444, 49 p

### Slope failure

**Issues**

- Debris flows in bajadas
- Debris flows are a response to cloud bursts (extreme, storm events)

**Importance to ecosystem**

- Slope failure on all slip faces of dunes

**Management significance**

- Debris flows don't affect park facilities (or visa versa)
- Managers know they exist but are of low concern because they don't affect park facilities

## Geothermal activity

NOTE: Participants decided not to rate this geoindicator because its importance to the ecosystem, human influence, and management significance are negligible. The geoindicator was not eliminated from the discussion because of its research and interpretation potential.

Groundwater and soil samples from the western boundary of the playa Lake Lucero were analyzed for chemical and microbial composition. DNA analysis revealed the detection of *Methanosaeta thermoacetophila*, a microbe diagnostic for deep, hydrothermal water. This discovery led to the hypothesis that hydrothermal water discharges into groundwater beneath Lake Lucero. Further support for this hypothesis is provided by (1) the presence of hydrothermal minerals in the soil, (2) abnormally high groundwater temperatures, and (3) a high $^{18}O$ isotope fractionation inconsistent with salinity effects alone. The inflow of hydrothermal water into an alkaline playa lake makes this area an extremely interesting study for origin of life theories.

Schulze-Makuch, D., 2002, Evidence for the discharge of hydrothermal water into Lake Lucero, White Sands National Monument, Southern New Mexico [abs.], *in* New Mexico Geological Society Guidebook, 53rd Field Conference, Geology of White Sands, p. 325.

ADDITION: It would be nice to know where these abnormally high groundwater temperatures in the basin are. Over the last 24 plus years, I have assisted several geothermal surveys at WSMR as a USGS employee and completed temperature logs on many wells and test holes up to several thousand feet deep throughout WSMR as a USGS and Army employee and have never seen anything as mentioned in this report. I have also talked to the noted experts on geothermal resources in NM and they do not know where these abnormally high temperatures occur in the Tularosa Basin (Bobby Myers, written communication, April 15, 2003).

**Issues**
- Limited evidence of geothermal waters in part of Lake Lucero
- Elevated temperatures in Garton Pond (31°C) from natural gradient, not geothermal activity

## Karst activity

**Issues**
- Visitor Center may be subsiding

**Human influences**
- Humans are causing a new process in the park
- Human induced dissolution of gypsum because of water pipe leaks
- Soil compaction because of weight of Visitor Center
- Parking lots are collapsing/sinking because of runoff-caused dissolution
- Water produces crystal growth on walls of adobe structures
- Evaporation coolers are not suitable for adobe structures

**Management significance**
- Stabilization of Visitor Center

- Cost of maintaining park facilities

## Sediment sequence and composition

Sediment sequence and composition has been identified as a significant and useful tool for enhancing the information base of the park's ecosystem, identifying human influences on the ecosystem, and providing data for management decisions and planning. Unlike the other geoindicators, sediment sequence and composition is not a geological process, but rather provides necessary background information and a past context of both natural processes and human activities. The chemical, physical, and biological character of aquatic sediments can provide a finely resolvable record of environmental change, in which natural events may be clearly distinguished from human inputs.

**Issues**
- Last 30,000 years are exposed in sediment in WHSA

**Management significance**
- Cores would provide baseline information for resource management and interpretation

**Inventory**
- McKee work, cross-section study of dunes
- High priority need at Lake Lucero to obtain history

## Appendix H: Compilation of Notes taken during Opening Session and Field Trips

### January 28 (Opening Session and Afternoon Field Trip)

### Opening Session (morning)

Welcome/Introductions (Jim Mack and Bill Conrod)

- White Sands National Monument (WHSA) was established in 1933 by presidential proclamation
- Alamogordo Bombing and Gunnery Range was established in 1941
- Less than 30 full-time employees in the Monument
- Park managers require help from regional offices because don't have all subject specialists on staff
- Park managers also seek assistance from universities
- Park managers desire graduate study proposals

Overview/Purpose (Bob Higgins)

- The purpose of the meeting is to infuse park thinking with geology
- This meeting is a first step for understanding the park's geologic resources
- Provide information that could be incorporated into the park's General Management Plan (GMP)

Geologic Overview (Rip Langford) (See also Appendix F)

- WHSA is part of a region with a complex and diverse geology
- It sits on the edge of a stable craton, i.e., the Great Plains Province
- It is part of the Basin and Range Province (the western U.S. has been "stretched")
- During the Permian Period (about 280 Ma), there was access out to the open ocean, Africa converged with N. America to create the Ancestral Rocky Mountains
- Permian was a time of tropical conditions, deep basins, and accumulation of mud and gypsum
- In the last 12-15 Ma, modern topography was developed, in particular, the Rio Grand Rift
- Basins are 2.5 km deep under the surface of sand at WHSA
- A large mountain-front fault formed during this time; the most recent movement has been in the last 5-15 thousand years
- Historic quakes were felt in 1887 and 1973 (6.5 and 7.3 magnitude)
- WHSA is on the Rio Grand Rift, flanked by the Sacramento and San Andres mountains
- In the last 30 Ma, the continent stretched; the region has been uplifted 4,000 feet in elevation; the whole of New Mexico and west Texas has domed up
- Rifting caused by lithospheric thinning
- East of rift is plains; west is Colorado Plateau
- 15 Ma, a chain of basins were created along with filling of basins from the Rio Grand River
- 3 Ma-650,000, WHSA became the low spot topographically and structurally; Rio Grand River shifted with respect subsidence and created a series of lakes, e.g., Lake Otero

- 1 Ma, faulting caused creation of divide, so river no longer flowed into the Tularosa Basin
- Basin floors are covered with old soils
- WHSA is very youthful (16-7 ky)
- Dunes began to form around 16,000 years ago
- Lakes are younger (had water later) than Lake Bonneville in Utah and have a different climate story
- In the last 15 million years, 2.5 km of sediment was deposited/formed
- Research potential: old lake basins, history of basin development (including clay)
- Research question: What really is "Lake Otero" (series of different lake surface elevations and shorelines)?
- Source of dunes: pluvial Lake Otero (50-60 feet deep)—preserved shoreline—lake dried and formed gypsum between 15,000 and 7,000 years ago

### Quaternary Geology (Curtis Monger)

- WHSA records a glacial-interglacial relationship; glacially-driven system; interglacials = aridity
- Rio Grand system, piedmont system, and aeolian system are part of the story
- Terraces are related to the Rio Grande; series of terraces; younger terraces have increasing calcium carbonate; calcium controls geomorphology; atmospheric deposition
- Charcoal deposits in soils are anthropogenic (40,000 years old)
- Ash deposits (Lava Creek)
- Pumice flows (Jimez volcanic field)
- Piedmont slope system consists of fans
- Aeolian system: winds from SW and blows across playa
- Coarse area between dunes, winnowing, lag deposits
- Change in landscape: grasslands (typical in 1800s) to shrublands (today)
- Middle Holocene aridity (12,000 to 10,000 years BP) had profound affect on plants-erosion
- 12,000 years ago—arid period; 10,000-9,000 years ago—pluvial period; 7,000-6,000 years ago arid, lakes drying out, followed by stable period; today—arid
- Jornada Basin (internally drained, sand dunes)—shows connection between climate change and landscape stability
- Grasslands represent landscape stability, also glacial periods
- Aridity may be linked to megafauna extinction, grasslands to shrubs
- Soil crusts in Monument: mosses, lichens, cyanobacteria—all are habitat related
- Human impacts: cattle grazing causes selective removal of particular kinds of plants and seed dispersal; mesquite grows in arroyos
- Overgrazing is a major factor in vegetative history

### Groundwater (Rick Huff)

- 25-35 Ma, formation of basin and range
- Basin is separated from Great Plains by Sacramento Mountains
- Formation of a series of basins that are aligned N-S, e.g., Tularosa Basin (called Waco/Hueco Basin in Texas)

- Upthrown sides of basin are Permian in age
- Fault-bounded mountains and faults in Tularosa Basin
- Groundwater flows from mountains to basins (Basin Fill Aquifer)
- 46 sub-basins surround Tularosa Basin
- Precipitation at high elevations in sub-basins produce groundwater recharge, especially from Sacramento Mountains
- In general, both groundwater and surface water moves away from the mountains, then south
- Hydrologically closed basin: 85% evapo-transpiration
- Rate of evaporation is 72 inches per year
- Depth to groundwater: near mountain front is >200 feet, basin center is about 25 feet below surface. CORRECTION: Depth to groundwater ranges from >200 feet near basin margins to <10 feet in central areas of the basin (Rick Huff, written communication, February 12, 2003)
- There is less sediment closer to the center of basin; therefore, closer to water, but also more saline
- At present, clastics are being shed off the mountains faster than it is being carried away
- Water quality: between 1,000 and 10,000 mg/L dissolved solids. CORRRECTION: Water quality ranges from <1,000 mg/L TDS to >10,000 mg/L TDS (Rick Huff, written communication, February 12, 2003)
- Better water quality closer to mountains
- There are two reservoirs of potable water: one exploited by Alamogordo and Holloman, the other by White Sands Missile Range
- Sulfides occur in basin center (gypsum); chlorides occur in playa lake area
- Dunes have chloride-dominated water; chloride is “left behind” during evaporation
- USGS has 6 wells in the Monument for monitoring groundwater quality—3 wells on the “Loop Road” and 3 wells behind the Admin. Building (wells 3, 4, and 5)
- ADDITION: The six USGS monitoring wells should be surveyed in and the lithology logs should be reviewed to determine what information might be obtained to supplement this information in any stratigraphic and hydrogeologic study of the Park. Also I am sure there have been multiple borings (some deep) drilled at Holloman AFB in the course of their environmental investigations that should be accessible (Pete Penoyer, written communication, February 24, 2003).
- Test for organic and inorganic constituents
- Lost River tested for perchlorate (from solid rocket fuel); sampling is tricky in ephemeral stream, therefore, try sampling salt cedar leaves
- Only Lost River showed signs of perchlorate (18 mg/L—3 orders of magnitude higher than California drinking water regulation); other wells sampled showed low amounts of contaminants
- Hydrazine detected in wells CORRECTION: Hydrazine detected in soil and groundwater at missile impact sites (Bill Conrod, written communication, February 25, 2003)

## Field Trip (January 28 afternoon and January 30)

Stop 1: Old Road—1860s Military Road (from Mesilla-Las Cruces to Ft. Stanton), stagecoach road

**Topics**: soil crusts, oryx, decomposition rates, sand movement

- Soil crusts are robust, recover quickly (within a few years) compared to Colorado Plateau, ecosystem dependent
- Sand movement (variable) depends on location within dune field and annual cycles
- Oryx: introduced in the 1960s to establish hunting population; removed 200 from Monument and are shooting the remaining ones; fence separates oryx from missile range and Monument (as well as native species); oryx are not being eliminated from missile range
- Decomposition rates in WHSA is comparable to a tropical rainforest
- Visitor impacts are minimal because of the restricted access

Stop 2: NE-30

**Topics**: geographic overview, dust storms, desalinization, plant succession

- Topographic high for Monument, above Pleistocene Lake Otero surface, old missile tracking station
- Western third of Monument is called "co-use zone"
- Lake Lucero playa to west (2 lakes); no outlet
- Seasonally, dust storms occur from mid-March to mid-May; winds from SW to NE
- San Andres NWR established in 1940 to protect bighorn sheep
- Alkali Flats—Space Harbor—emergency landing strip for space shuttle
- Salinas Peak (about 9,000 feet) is high point of missile range
- Sierra Blanca (about 12,000 feet)
- Desalinization plant proposed at the base of Sierra Blanca; could cause indirect effects, e.g., population growth
- Dune field: monitoring wells, perched aquifer, level of capillary action controls dunes in the area
- Alamogordo has catchment basins on streams up to 8,000 feet in elevation and has dewatered all streams
- Garton Pond (east of Highway 70) drilled well (1920s); encountered warm water and created 5 acre pond; also wildlife habitat; dried up in the 1970s, now just a seep
- ADDITION: I thought Garton Pond resulted from an abandoned oil exploration drill hole that encountered warm artesian water. The well was not abandoned appropriately and continued flow to the surface creating a wildlife habitat. It began to dry up in the 70's after an attempt to dynamite the well bore. This damaged the connection to the aquifer, flow diminished over time and the pond largely dried up in the 1970's (Pete Penoyer, written communication, February 24, 2003) CORRECTION: Actually the discharge slowed to a trickle, resulting in an attempt to increase flow by blasting (always dumb), which may have further reduced the discharge (Bill Conrod, written communication, March 13, 2003).
- Cresote grows on sandy soils (e.g., alluvial fans)
- Tar brush grows on silty soils (e.g., lake beds)
- Salt tolerant shrubs grow on playa lakes

## Stop 3: Lake Lucero area

**Topics**: gypsum, DNA, dune formation

- Hand dug well (pre-1911), cattle ranch site
- Selenite crystals form in disks at the mud-water interface; when wind deflates area, they become exposed
- Selenite (Pleistocene deposits)
- There is little or no dune formation at present, just dune migration; seems that water table is too high now
- Lake Lucero may serve as a potential template for “origin of life” theories; geothermal waters and DNA detected; proteins can adhere to crystal structure
- 3 periods of dune formation: early Holocene, 6,000-7,000 years ago, 4,000-1,000 years ago

## Stop 4: Small playa/deflation basin

**Topics**: playa, annual rainfall, Loop Road

- Receive half of the annual precipitation in July and August (about 8 inches per year)
- Playa is frequently wet in the summer
- Spade foot toads used to be “everywhere”—breeding cycle to larval stage in hours; tiger salamanders also in dunes
- Parabolic dune field: low and semi-vegetated
- Archeological sites: Indians harvested rice grass, pedestal sites, charcoal, chipped rock sites
- Sand blowing across road is a continual maintenance project, half of 1 FTE’s job
- Road alignment has shifted over time
- Park did programmatic EA to maintain road
- Saltation occurs at 17 mph, sand avalanches down slip face
- “Avalanche structures” in interdunal area

Additional stops on January 30, 2003:

**Topics**: dewatering (Dog Canyon in Oliver State Park has not been dewatered, constant stream, 10-30 cfs), water used for grazing, domestic use/population growth because of military base; selenite collection on White Sands Missile Range; space shuttle landing strip; Lost River (culverts, pup fish)

## Appendix I: Paleontological Resources at White Sands National Monument

Currently there are no documented paleontological resources from within the boundaries of White Sands National Monument (WHSA). This is not surprising, as there have never been any systematic or organized efforts to document fossils within the Monument.

Pleistocene fossil vertebrates and molluscs have been found at a number of localities in White Sands Missile Range just north of the Monument (Morgan and Lucas, 2002). These fossils were recovered from clays and gypsiferous clays of the Otero Formation. The Otero Formation was deposited in a large pluvial lake, Lake Otero, which covered a large portion of the Tularosa basin (Lucas and Hawley, 2002). Lake Lucero in the Monument is a remnant of Lake Otero and lake sediments similar to those in the missile range are present in the northwest part of the monument. It would therefore not be unexpected that lake sediments within the Monument would also contain Pleistocene vertebrates, invertebrates, and plants.

While larger fossils such as bones of mammoths, bison or horse may be more easily observed, these lake sediments will also contain microfossils. While not easily observed when properly collected and processed microfossils such as ostracodes or diatoms could provide important paleoecological information. Ostracodes are small, bivalved crustaceans, usually less than 2 mm in size, which have long been used as indicators of paleoecological settings and paleoenvironmental change. Diatoms are microscopic algae with a siliceous shell that is easily preserved. Any survey and documentation of fossil resources within the monument should take into account the potential of micro as well as macrofossils.

Because of security precautions at White Sands Missile Range, exposures of Pleistocene Lake Otero have not been as accessible as those of pluvial lakes in other basins in New Mexico. Consequently our knowledge of the history of this Pleistocene pluvial lake is not as extensive as that of Lake Estancia to the north. Recent studies at Lake Estancia (Allen, 1996; Bachhuber, 1990; Behnke and Platts, 1990; Frenzel et al., 1992) have demonstrated the wealth of climatic data that can be obtained from these lake sediments. Similar studies of Lake Otero sediments would provide similar valuable information. While the portion of Lake Otero sediments preserved at WHSA is small compared to the overall size of the lake, the monument part of the story is particularly critical because it would preserve the latest part of the history of Lake Otero, particularly with its progressive decrease in size to its remnant, Lake Lucero. In additional to providing critical information on the geological history of the park and the formation of its primary resource—the sand dunes—a knowledge of the history of Lake Otero would provide an important framework for understanding the paleoecological context for early people in the basin, paleoindians and archaic cultures. As such a study of the Lake Otero sediments and recovery of associated fossil resources can enhance our understanding or many other park resources.

In addition to the body fossils recovered from the sediments, there is also the possibility that trace fossils, the tracks of extinct Pleistocene vertebrates such as mammoths, camels and horses may be found within the Monument. Lucas et al. (2002) have documented the tracks of extinct Pleistocene vertebrates with unusual preservation at White Sands Missile Range just north of the monument. The tracks are preserved in convex relief in a soft gypsum matrix. They are extremely fragile and easily eroded. As part of a survey of paleontological resources in the

Monument, there should be an awareness of the potential for the existence of similarly preserved tracks.

Recommendations

- Conduct a preliminary survey to determine presence of paleontological resources in the Monument. Paleontologists at the New Mexico Museum of Natural History and Science have expressed an interest in providing this survey for fossil vertebrates and larger invertebrates. The survey could be funded through the NPS Geoscientists-in-the-Parks (GIP) program.
- Collect samples for preliminary determination of presence of fossil micro invertebrates in Lake Otero sediments in the northwest corner of the park. Bruce Allen of the New Mexico Bureau of Mines has expressed interest in this project. This project could also be funded through the GIP program.
- Based on results of the preliminary studies, the park could be involved in a larger Lake Otero Basin study which would be a cooperative project between the New Mexico Museum of Natural History and Science, New Mexico Bureau of Geology and Mineral Resources, White Sands Missile Range, and White Sands National Monument. The goal of the project would be to look at the paleoecology and paleontology of the basin related to climatic change during the Pleistocene.

References

Allen, B.D., 1996, The late Pleistocene climate record from Estancia basin, New Mexico: Presentation to the Albuquerque Geologic Society, October 6.

Bachhuber, F.W., 1990, The occurrence and paleolimnologic significance of cutthroat trout (Oncorhynchus clarki) in pluvial lakes of the Estancia Valley, central New Mexico—discussion and reply: Geological Society of America Bulletin, v. 102, p.1731-1732.

Behnke, R.J. and Platts, W.J., 1990, The occurrence and paleolimnologic significance of cutthroat trout (Oncorhynchus clarki) in pluvial lakes of the Estancia Valley, New Mexico—discussion and reply: Geological Society of America Bulletin, v. 102, p.1731-1732..

Frenzel, B. et al., 1992, Climates during the last glacial maximum, *in* Frenzel, B., Pecsi, M., and Velichko, A.A., eds., Atlas of paleoclimates and paleoenvironments of the northern hemisphere, late Pleistocene-Holocene: Geographical Research Institute, Hungarian Academy of Sciences, p. 97-99.

Lucas, S.G. and J.W. Hawley, 2002, The Otero Formation, Pleistocene lacustrine strata in the Tularosa Basin, Dona Ana County, New Mexico, *in* V.W. Lueth, K.A. Giles, S.G. Lucas, B.S. Kues, Myers, R., and Ulmer-Scholle, D.S., eds., Geology of White Sands: New Mexico Geological Society Fifty-third Annual Field Conference, p. 277-284.

Lucas, S.G., Morgan, G.S., Hawley, J.W., Love, D.W., and Myers, R.G., 2002, Mammal footprints from the upper Pleistocene of the Tularosa Basin, Dona Ana County, New Mexico, *in* Lueth, V.W., Giles, K.A., Lucas, S.G., Kues, B.S., Myers, R., and Ulmer-Scholle, D.S., eds., Geology of White Sands: New Mexico Geological Society Fifty-third Annual Field Conference, p. 285-288.

Morgan, G.S. and Lucas, S.G., 2002, Pleistocene vertebrates from the White Sands Missile Range, southern New Mexico, *in* Lueth, V.W., Giles, K.A., Lucas, S.G., Kues, B.S., Myers, R., and Ulmer-Scholle, D.S., eds., Geology of White Sands: New Mexico Geological Society Fifty-third Annual Field Conference, p. 267-276.

Prepared by Greg McDonald, National Park Service, Geologic Resources Division, greg_mcdonald@nps.gov, 303-969-2821

## Appendix J: Comments on Appendix F, “Park Geological Setting”

**Comments from Dave Love, New Mexico Bureau of Geology and Mineral Resources (February 26, 2003):**

Let the New Mexico Bureau of Geology help [with interpretive materials like this one]. Last year’s volunteer did not have benefit of new guidebook. Bill Raatz has a nice summary (for geologists) in the New Mexico Geological Society guidebook “Geology of White Sands,” pp.141-157.

Fixes for now:

I would start with introduction to geography of area and concept of geologic time--see our Scenic Trip # 15.

Permian sea

1. The Permian Sea
The gypsum that makes up White Sands is ultimately derived from marine rocks. Shallow seas covered much of *southern* New Mexico throughout the Paleozoic Era (*543-248*) million years ago. Marine deposits as old as 500 million years are present in the San Andres Mountains, but by far the most abundant sedimentary rocks in southern New Mexico are Permian in age (290-248 Ma). In the Permian Period North America was part of a great megacontinent called Pangaea, and present day New Mexico was submerged in a tropical sea just *north* of the equator (Figure 1). The limestone mountains at Carlsbad Caverns and Guadalupe Mountains National Parks represent the remains of a large barrier reef that was part of this Permian sea. *Behind the reef to the northwest was a broad shelf which was episodically flooded by shallow seawaters. In the middle of the Permian Period the sea water in shelf area repeatedly evaporated to deposit large quantities of gypsum rock.*

Suggest two minor changes in Gypsum paragraph
change "will be" to "are"
change "outcrops" to "crops out"

2. Laramide Uplift
This needs work. I would recommend removing plate tectonics from here and having separate section on plate tectonic setting of southern New Mexico through time. Number of major plates and their configuration has changed through time, as has the geographic setting of New Mexico (from south of the equator to north of 45 degrees and back to present location).

Laramide involves both big uplifts and basins across New Mexico and probably some strike-slip faulting as well. Mention is made of Jurassic and Cretaceous periods in relation to plate tectonics, but not in relation to White Sands geologic history.

If Laramide is important to White Sands (which it is, regionally) one should mention where the uplifts and basins are relative to White Sands (map would help).

There should be some justification for last statement about elevation of southern NM. Similarly, sections 3, 4, and 5 need some expert aid. I'm concerned about discussion of timing of Tularosa basin, Pleistocene lakes, and formation of dunes. Rip Langford has an article in the White Sands guidebook to help with some of the issues.

I think it would be worthwhile to have a brief discussion about current issues relative to what the visitor sees at White Sands--consequences of global climate change (wet or dry) relative to dunes; water issues; impact of humans on park conservation efforts; natural hazards such as dust storms, earthquakes, volcanic eruptions, debris flows, ...

Comments provided by Dave Love, New Mexico Bureau of Geology and Mineral Resources, dave@gis.nmt.edu, 505-835-5146

**Comments from Steve Fryberger (March 8, 2003) on "Dune Formation" section:**

Here is some rough copy (see Appendix F) that tries to capture a few of my thoughts vis a vis the draft text that was forwarded to me by Bill Conrod (February 26, 2003). I am just not fresh enough on Brenda Buck's material to roll out the dates that she got, but it's in her thesis and in my commentary—the Quaternary geology chapter. I attach the topographic map of White Sands that I hope illustrates that the fossil dunes are certainly high enough to have been formed at almost anytime in the basin history (see below). You might want to check the Lake Estancia fill pattern documented by people at the NM Bureau of Mines and Mineral Resources (see references below). I have tried to at least provide you with some language that you can adopt, modify, etc. as appropriate for your readers. Truth is, we need more dates. Note that I attach the topographic map as a powerpoint slide.

I include some references from the work of Bruce Allen and Bur. Mines that set up the cycles for Lake Estancia, north of White Sands. The patterns at this like probably followed White Sands closely, although the elevation is higher. You might wish to have a look at the 119 paper (brilliant) and the field guides.


Allen, B.D.,1991, Effect of climatic change on Estancia Valley, New Mexico: Sedimentation and landscape evolution in a closed-drainage basin, *in* Julian, B., and Zidek, J., eds., Field Guide to geologic excursions in New Mexico and adjacent areas of Texas and Colorado, New Mexico Bureau of Mines and Mineral Resources Bulletin 137, p. 166–171.

Allen, B.D., 1994, Ancient Lakes: A tool for Understanding Climatic Change, Lite Geology, Summer 1994.

Allen, B.D. and Hawley, J.W., 1991, Day 2, Part 2: Lake Estancia basin tour, *in*, Julian, B., and Zidek, J., eds., Field Guide to geologic excursions in New Mexico and adjacent areas of Texas and Colorado, New Mexico Bureau of Mines and Mineral Resources Bulletin 137, p. 130–133.
Allen, B.D. and Anderson, R.Y., 1993, Evidence from Western North America for Rapid Shifts in Climate During the Last Glacial Maximum, Science, vol. 260, p. 1920–1923.

A Portion of the 1-100,000 metric topographic map of white sands